RL-TR-95-130
Final Technical Report
July 1995

VHF/UHF LOW PROFILE ANTENNA ANALYSIS

Georgia Institute of Technology

J. Dayton Adams, Rickey B. Cotton, and Victor K. Tripp

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

Rome Laboratory
Air Force Materiel Command
Griffiss Air Force Base, New York

This report has been reviewed by the Rome Laboratory Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

RL-TR-95-130 has been reviewed and is approved for publication.

APPROVED:

KENNETH R. SIARKIEWICZ
Project Engineer

FOR THE COMMANDER:

JOHN J. BART
Chief Scientist, Reliability Sciences
Electromagnetics & Reliability Directorate

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1995	Final Jul 93 - Dec 93

4. TITLE AND SUBTITLE

VHF/UHF LOW PROFILE ANTENNA ANALYSIS

5. FUNDING NUMBERS

C - F30602-93-C-0220
PE - N/A
PR - R468
TA - 00
WU - P1

6. AUTHOR(S)

J. Dayton Adams, Rickey B. Cotton, and Victor K. Tripp

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Georgia Institute of Technology
Georgia Tech Research Institute
Atlanta GA 30332

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Rome Laboratory (ERST)
525 Brooks Rd
Griffiss AFB NY 13441-4505

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

RL-TR-95-130

11. SUPPLEMENTARY NOTES

Rome Laboratory Project Engineer: Kenneth R. Siarkiewicz/ERST/(315) 330-2465

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report describes the results of an analytical and experimental study to determine the feasibility of developing octave bandwidth, electrically small, low profile antennas in UHF and VHF bands from 20 to 1200 MHz. The combination of achieving both small size and octave bandwidths in the frequency range from 20-160 MHz presents the most difficult challenge. Antenna elements examined include loops, disk-cones, conical monopoles, Goubau, and microstrip spiral antennas. Results presented include experimental data on disk-cones, a scaled conical monopole, and a scaled microstrip spiral antenna. More work remains to be done, especially in the 20-40 MHz band. However, it is projected that, with continued development efforts, the desired results can be achieved.

14. SUBJECT TERMS

Antenna, UHF, VHF, Low profile

15. NUMBER OF PAGES 76

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

FORWARD

This final technical report describes the work performed under Contract F30602-93-C-0220, Project Number N-3-5538, during the period from 26 July 1993 to 25 December 1993.

The work on this contract was performed by the Antenna Technology Development Division of the Georgia Tech Research Institute (GTRI) at the Georgia Institute of Technology, Atlanta, Georgia under Project A-9520. Mr. K. Sierkiewicz (ERPT) was the RADC Project Engineer.

In addition to the authors, contributors to the work described herein include Messrs Chris Papanicolopulos and Royce Byrd, and Dr. Ed Joy. Ms. Diane Aenchbacher prepared the manuscript.

Accesion For	
NTIS CRA&I	X
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and / or Special
A-1	

TABLE OF CONTENTS

SECTION 1
INTRODUCTION
. . . . 1

1.1 REQUIREMENTS 1

1.2 TECHNICAL APPROACH 2

1.3 CANDIDATE ANTENNA ELEMENTS 3

SECTION 2
CANDIDATE ANTENNA ELEMENT EVALUATIONS
. . . . 4

2.1 TUNABLE LOOPS 4

2.2 MICROSTRIP SPIRALS 7
2.2.1 Background 7
2.2.2 Basic Design Principles for the Spiral-Mode Microstrip Antenna 8
2.2.3 Experimental Results 9
2.2.4 Summary of Results 11
2.2.5 Use of Special Substrate Materials 12

2.3 DISKCONE ANTENNAS 13

2.4 CONICAL MONOPOLES 17

2.5 GOUBAU ANTENNA 19

SECTION 3
SYSTEM AND PACKAGING CONSIDERATIONS
. . . . 51

TABLE OF CONTENTS (continued)

SECTION 4
CONCLUSIONS AND RECOMMENDATIONS
. . . . 56

SECTION 5
REFERENCES
. . . . 58

LIST OF TABLES

Table 1-1. Frequency Ranges and Associated Gains for Individual Bands 1
Table 2-1. Specifications of Isoloop Model 10-30 Antenna 5
Table 2-1. Estimated Microstrip Spiral Performance with Ferrite Materials 13
Table 3-1. Candidate Antenna Elements with Sizes and Volumes for Various Bands 52
Table 3-2. System Configuration Option No. 1 53
Table 3-3. System Configuration Option No. 2 53

LIST OF FIGURES

Figure 2-1. Return loss measurement for IsoLoop antenna adjacent to a ground plane. 21
Figure 2-2. Return loss measurement for IsoLoop antenna elevated 60" relative to a ground plane. 22
Figure 2-3. Return loss measurements for IsoLoop antenna elevated above a ground plane while tuning the antenna for different frequencies. 23
Figure 2-4. Experimental set-up for two-arm spiral. 24
Figure 2-5. Method of feeding two-arm spiral and placement of absorber. 25
Figure 2-6. Measured peak gain versus frequency for a two-arm spiral without absorber and a ground plane spacing of 0.070 inch. 26
Figure 2-7. Measured peak gain versus frequency for a two-arm spiral without absorber and a ground plane spacing of 0.145 inch. 27
Figure 2-8. Measured peak gain versus frequency for a two-arm spiral without absorber and a ground plane spacing of 0.220 inch. 28
Figure 2-9. Measured peak gain versus frequency for a two-arm spiral with absorber and a ground plane spacing of 0.070 inch. 29
Figure 2-10. Measured peak gain versus frequency for a two-arm spiral with absorber and a ground plane spacing of 0.140 inch. 30
Figure 2-11. Measured peak gain versus frequency for a two-arm spiral with absorber and a ground plane spacing of 0.228 inch. 31
Figure 2-12. Measured peak gain versus frequency for a two-arm spiral with absorber and a ground plane spacing of 0.240 inch. 32
Figure 2-13. Gain versus scaled and actual frequency for a two-arm spiral with absorber and vertical polarization. 33
Figure 2-14. Gain versus elevation angle for un-optimized two-arm spiral antenna. 34
Figure 2-15. Experimental set-up for four-arm spiral. 35
Figure 2-16. Method of feeding four-arm spiral. 36
Figure 2-17. Measured gain versus frequency for a four-arm spiral with a ground plane spacing of 0.071 inch and no absorber present. 37
Figure 2-18. Measured gain versus frequency for a four-arm spiral with a ground plane spacing of 0.143 inch and no absorber present. 38
Figure 2-19. Measured gain versus frequency for a four-arm spiral with a ground plane spacing of 0.214 inch and no absorber present. 39
Figure 2-20. Measured gain versus frequency with vertical polarization for a four-arm spiral with a ground plane spacing of 0.240 inch and no absorber present. 40

LIST OF FIGURES (continued)

Figure 2-21. Gain versus elevation angle for four-arm spiral at 8 GHz. 41
Figure 2-22. Return loss of diskcone antenna with and without ground plane. 42
Figure 2-23 Diskcone antenna data for test antenna used to determine interaction of diskcone antenna radiation patterns when located near a ground plane. 43
Figure 2-24. Return loss of diskcone antenna in free space and on a ground plane. 44
Figure 2-25. Return loss of diskcone antenna at various heights above ground plane. 45
Figure 2-26. Design dimensions for diskcones operating in bands C,D,E and F. . . 46
Figure 2-27. Return loss measurement of conical monopole. 47
Figure 2-28. Conical monopole pattern predictions from Baker and Botha [18]. . . . 48
Figure 2-29. Schematic illustration of the Goubau antenna. 49
Figure 2-30. Return loss of Goubau antenna test article. 50
Figure 3-1. Block Diagram of Option No. 1 System 54
Figure 3-2. Block Diagram of Option No. 2 System 55

SECTION 1

INTRODUCTION

1.1 REQUIREMENTS

The Georgia Tech Research Institute (GTRI) performed this study for the Special Programs and Advanced Technology Division of the Naval Explosive Ordnance Disposal Technology Center at Indian Head, Maryland. The Navy has a requirement to develop a 20 MHz to 1200 MHz low profile antenna system for both mobile and fixed site applications. The antenna system must have a low profile, be mounted on a ground plane with maximum dimensions 96 inches long by 48 inches wide, and be no more than 24 inches high. The system must operate in both transmit and receive modes. The Navy desires to cover the 20 MHz to 1200 MHz range with six antenna elements, each having approximately an octave bandwidth. Vertical polarization with elevation coverage (at specified gains) of -10 to +20 degrees is required. The required gain and bandwidth of each element are shown in table 1-1. Transmitter output will be 50 watts CW, which defines the power handling requirement of the antenna elements.

Table 1-1. Frequency Ranges and Associated Gains for Individual Bands

Band	Desired Gain, dBi	Frequency Range, MHz
A	-10	20.000 to 39.999
B	-5	40.000 to 79.999
C	-1	80.000 to 159.999
D	0	160.000 to 319.999
E	0	320.000 to 599.999
F	+1	600.00 to 1200.000

For the most part, each element covers approximately 1 octave of bandwidth. Each element must be capable of both transmitting and receiving, but not both simultaneously. Up to five distinct frequencies, per band, may be transmitted at one time. This requirement precludes the use of tunable elements which have very narrow instantaneous bandwidths.

The gains shown in table 1-1 are desired minimum gains over the -10 to +20 degree elevation sector (higher gains are permissible but minimum gains should be no more than 1 dB less than that shown). The required polarization is vertical. The gain and polarization requirements taken together mean that the gain of the vertical component of the radiation pattern shall be as specified in table 1-1; there is no other limitation on the horizontal component. Also, the elevation coverage requirement imposes no limit on the radiation outside the -10 to +20 degree range.

1.2 TECHNICAL APPROACH

Critical issues in meeting the Indian Head requirements include: (1) achieving octave performance at the lower frequency bands with the electrically very small antennas, (2) isolating the transmit and the receive elements, (3) elevation angle coverage, (4) power handling, and (5) overall packaging. To address these issues, GTRI's approach consisted of the following tasks:

Task 1. Perform a literature search and study to identify potential antenna candidates.

Task 2. Perform analytical study to determine predicted performance of selected candidates. Perform a tradeoff study considering such performance factors as size, gain, elevation coverage, vehicle interaction, bandwidth, and power handling ability.

Task 3. Breadboard selected antenna elements to validate performance predictions.

Task 4. Postulate system configuration.

Task 5. Perform a packaging study, define size limitations.

Task 6. Document results in a technical report and final technical briefing.

It should be recognized that the objective of this effort was to evaluate candidate antenna elements and determine if a potential solution to the Navy's requirements exists. It was recognized that it would be difficult to simultaneously satisfy all goals. The generation of final antenna element designs was not a part of this effort.

1.3 CANDIDATE ANTENNA ELEMENTS

Prior to initiation of this program, GTRI had identified four antenna elements to be considered in the initial study phase. These initial candidate antenna elements were: the loop [1, 2], bi-conical antennas [3], whips [4], and the spiral-mode microstrip antenna [5,6]. Results of the literature search, specifically a report by DeSantis [7], lead to the addition of the disk-cone and Goubau antennas to the list of candidates. It was recognized that the loop antenna had limitations resulting from small resistance, high Q, and small instantaneous bandwidth, but because of its relatively small size and low profile, it was thought that multiple tuned loops might be used in band A. After a brief evaluation of tunable loops, this approach was discarded due to the absence in the operational system of *a priori* frequency information for loop tuning. However, the collected and measured data on tunable loops are included herein for completeness and also because tunable loops might be used in other applications.

SECTION 2

CANDIDATE ANTENNA ELEMENT EVALUATIONS

2.1 TUNABLE LOOPS

An antenna for consideration to meet part of the present requirements is the loop antenna which is similar to a magnetic dipole antenna. Loop antennas can exist in various sizes, electrically large, which are typically one λ in circumference, and electrically small loops, typically $\lambda/4$ or less in circumference. The smaller loop antennas offer a compact structure, with narrow instantaneous bandwidth. However, these antennas are tunable over an octave or more of bandwidth.

A tunable loop antenna is relatively electrically small, with the circumference of the antenna being approximately 0.1λ at the lowest frequency and 0.3λ at the upper frequency. This antenna is constructed of a conductor formed into the shape of a loop, with a tuning capacitor welded in series with the loop to form a resonant antenna. The antenna loop is excited by a inductively coupled coaxial loop. Tuning the loop antenna is accomplished by varying the capacitance of the variable capacitor to tune the Q of the circuit as the frequency is changed. This tuning is typically accomplished by a stepper motor or dc motor connected to a remote control. The capacitor and loop provide a high Q resonant circuit which is tunable by adjusting the capacitance. The tuning capacitor is welded to the loop to minimize loss and is sized sufficiently to handle the high voltage across the capacitor plates.

A tunable loop antenna known as the IsoLoop antenna was purchased from Advanced Electronic Applications Inc. for evaluation. This antenna has specifications shown in table 2-1.

Table 2-1. Specifications of Isoloop Model 10-30 Antenna

Frequency Coverage	10 to 30 MHz
Nominal Impedance (tuned)	50 ohms
Power Rating	150 watts
VSWR	<1.4:1 (no nearby objects)
Dimensions	35" diameter, 38.8" housing
Weight	25 pounds
Connector	UHF (SO-239)
Gain	2.14 dB

The antenna was initially evaluated by measuring its return loss. The antenna was placed on a table top and the return loss measured. Measured data are shown in figure 2-1. With tuning, the return loss varied from 2 dB to 5 dB, at best. Once the antenna was elevated approximately 60" above the nearest surface, the return loss improved considerably. The return loss improved to better than 17 dB, and the bandwidth, defined by a 2.0:1 VSWR, is approximately 125 KHz, as shown in figure 2-2. Figure 2-3 shows repeated measurements of the return loss of the antenna as the antenna is tuned from the lower frequency band edge to the upper band edge. The return loss varied from 2 dB worst case, to 23 dB at best, and averaged approximately 10 dB, as suggested by the specifications. Due to the poor performance of the antenna when placed adjacent to a ground plane, no further tests on this antenna were performed.

Even though the IsoLoop antenna performed poorly for this application, loops should not be precluded from use in this system. For example, consider an 8" diameter, UHF loop antenna commonly associated with television broadcast which operates satisfactorily over

the UHF TV broadcast band of 470 to 890 MHz. The loop circumference is approximately 25", which corresponds to a circumference of 1λ at the lowest frequency and 1.9λ at the highest frequency. This antenna is operated above its first anti-resonance frequency and slightly beyond its resonance frequency. Across the 1.0 - 1.9 wavelength band, the VSWR with a 300-ohm feed line is less than 3:1.

The circumference of the loop antenna increases as the frequency decreases; for example, at 30 MHz, the diameter of a loop would be 10.4 feet. This loop would radiate over a octave bandwidth, but the size is impractical for the application in this study. At lower frequencies, as one tries to shrink the size of the loop, the performance is adversely affected as illustrated by the IsoLoop antenna performance. For these conditions, the operational bandwidth decreases, and the radiation resistance decreases, which required welding the tuning capacitor to the loop. However, a 1/2λ loop on a ground plane can be used to replace the full wavelength diameter antenna in free space previously discussed. The shape of the half-loop antenna can be altered to an acceptable configuration. For example, a rectangular half-loop may be substituted for a half-circle loop with little change in performance as long as the perimeter remains constant. However, as the loop height is reduced significantly relative to the wavelength, the antenna behaves as a highly reactive, non-radiating, short-circuited transmission line antenna with narrow instantaneous bandwidth. In a similar program at GTRI, a 12" x 24" half-loop above ground was simulated and the impedance calculated by the method-of-moments. The loop conductors were assumed to be 1" in diameter and lossless. The simulation indicated that the antenna could be matched to obtain a 2.5:1 VSWR from 120 to 250 MHz. By doubling the size of the loop, anticipated performance could be lowered to 60 MHz. This concept requires further evaluation, but it could be adapted to the current required volume constraints. With this configuration, two loops oriented 90° relative to each other would be required to provide full azimuth coverage due to the null in the antenna pattern of a single loop.

2.2 MICROSTRIP SPIRALS

2.2.1 Background

The planar spiral-mode antennas, such as the equiangular type [8] and the sinuous antennas [9], have multi-octave frequency bandwidths. Unfortunately, they radiate to both sides of the spiral plane, whereas applications generally require a unidirectional pattern. To overcome this difficulty over a large frequency bandwidth, the usual approach is to place a lossy cavity on one side of the spiral or sinuous structure to absorb all the undesired radiation in that direction. This cavity-backed planar spiral was perfected more than a decade ago, achieving typically a 9:1 frequency bandwidth of, say, 2-18 GHz.

The lossy cavity of the spiral and sinuous antennas has two undesirable effects: 1) at least half of the radiated power is lost in the dissipative cavity, and 2) the cavity is deeper than the radius of the spiral and therefore not suitable for low-profile surface mounting.

It has been recognized, however, that the planar spiral can be designed with the backing of a lossless cavity [10] or a conducting plane [11] to achieve a bandwidth of 40 or 20%, respectively.

When low profile and conformability are of primary concern, the microstrip antenna [12] is generally the antenna of choice and has been widely used. However, existing microstrip antennas are typically limited to a narrow bandwidth. Wood [13] initially investigated this possibility of broad-banding by using a single microstrip line wound as an Archimedian spiral. Wood concluded that the achievement of a wide band analogous to the conventional spiral was not feasible because the radiation patterns tend to exhibit a large axial ratio. Subsequently, experimental efforts were conducted at GTRI [14]. It was found that impedance matching deteriorated as the substrates became thinner and the ground

plane was placed closer to the spiral. Yet even when the substrate was only 1/16-in thick, a return loss below 10 dB (or a voltage standing-wave ratio (VSWR) lower than 1.92) was observed over the wide frequency range of 6-16 GHz.

Although the impedance data were impressive, poor patterns, as found by Wood, lead to halting the work. Recent work at GTRI has lead to advancement in these antennas so that their use here is now feasible [5,6].

2.2.2 Basic Design Principles for the Spiral-Mode Microstrip Antenna

The basic planar spiral antenna, which consists of a planar sheet of an infinitely large spiral or sinuous structure, radiates on both sides of the spiral in a symmetric manner. When radiating in the $n = 1$ mode, most of the radiation occurs near a circular ring around the center of a spiral whose circumference is about one wavelength. As a result, one can truncate the spiral outside this radiation ring without too much effect on the radiation pattern.

In practical applications, there is virtually no need for a spiral radiating on both sides of the spiral plane. In a cavity-backed planar spiral, one side of the radiated power is absorbed by a lossy cavity, otherwise the undesired radiation on the cavity side may interfere with the desired radiation on the other side.

When a ground plane is placed behind a planar spiral antenna, its interference with the radiation pattern has long been recognized, even though little documented. Theoretically, analysis shows that as far as the spiral radiation is concerned, a ground plane appears quite tolerable. The analysis also shows that the effects of dielectric backing are detrimental, and therefore the dielectric constant of the substrate should be kept low.

A simple technique to remove the residual power is to place a ring of absorbing material at the truncated edge of the spiral outside the radiation zone. This scheme allows the absorption of the residual power which would radiate in an n = 1- mode (opposite sense CP) and n = ±2 modes, causing drastic deterioration of radiation patterns, especially at off-boresight angles.

2.2.3 Experimental Results

Since fabricating a microstrip spiral antenna to operate at 20 MHz and cover the available 48-inch diameter ground plane would have been too costly and time consuming, it was decided to use frequency-scaled measurements instead. In frequency scaling, it is approximately correct to scale antenna size inversely by the ratio of test frequency to desired frequency. Therefore, if we want to determine antenna operating characteristics at 20 MHz, we can build a test antenna which is 1/50th the actual size and test it at 1000 MHz. For the present measurements, we used a 1-inch diameter test antenna, which is about 1/50th the maximum allowable antenna diameter. For this antenna, the spiral-to-ground plane spacing scales by the same factor. Figure 2-4 illustrates the experimental set-up for the two- arm spiral (mode 1 operation). A similar set-up was used for mode 2 operation with a four- arm spiral. Figure 2-5 shows the method for feeding the two-arm spiral and the placement of absorber for tests with absorber present. Purposes of the measurements were to (1) determine the variation of peak gain with frequency for both modes 1 and 2, (2) determine the variation of gain with angle relative to the horizon, and (3) determine the lowest frequency at which this antenna would meet performance specifications.

As shown in figure 2-4, the antenna-to-ground plane spacing may be varied. In practice, the antenna position was fixed and the ground plane was moved in and out relative to the antenna. A series of gain versus frequency measurements was performed at various ground plane spacings, both with and without absorber present as indicated in figure 2-5.

Figures 2-6 through 2-12 shows gains versus frequency for various ground plane spacings, both without absorber and with absorber placed as in configuration number 2 in figure 2-5. Notice that there are three curves on each figure. The test antenna's matched polarization is circular, but the probe antenna was linearly polarized. Hence, the Pmax and Pmin curves represent the polarization orientation of the probe antenna for maximum and minimum response, respectively. The curves labeled Match Pol. represent what the response would have been if the probe antenna's polarization was matched to that of the test antenna. The curves presented cover a frequency range of 2.0-6.0 GHz (this antenna operates well up to at least 12 GHz). Figure 2-13 presents a re-plot of these data for vertical polarization along with an axis for direct reading of the scaled frequency of a 50-inch diameter spiral. A main point of these tests was to determine the lowest frequency at which this antenna no longer provides sufficient gain. Recall that this is a 50:1 scaled antenna, and from table 1-1, the minimum gains in Bands A and B are -10 dBi and 5 dBi, respectively. The gains shown in figures 2-6 through 2-13 are peak elevation gains, which will decrease at the horizon. Figure 2-14 presents gain versus elevation angle for another spiral antenna. Here, gain at the horizon decreases by 15 dB from the peak gain. With proper techniques, it is believed that this gain decrease can be limited to 10 dB. Thus, the lower frequency bound for the experimental antennas is taken to be the point at which the measured gain falls to 0 dBi. For low frequency performance, the best configuration for the two-arm spiral appears to be with absorber present and a ground plane spacing of 0.228-inch to 0.240-inch. For these cases, the measured lower frequency limit is seen to be 3.0 GHz, which scales to 60 MHz for the 50-inch diameter antenna.

To investigate whether or not spiral operation in mode two would increase gain at the horizon for an equal size antenna, a four-arm spiral was fabricated and tested. Figures 2-15 and 2-16, respectively, show the experimental set-up and the method of feeding the four-arm spiral. Figures 2-17 through 2-20 show peak gains versus frequency, without absorber. These curves are analogous to the ones previously presented and described

for Mode 1. Measurements with absorber have not been completed for the four-arm spiral. Figure 2-21 shows measured gain versus elevation angle for this four-arm spiral operating at 8 GHz. As was the case for mode 1, the measured gain at the horizon is about 15 dB below the peak gain, which in this case occurs at a 45 degree elevation angle. By comparison, it is seen that the 0 dB gain point for the four-arm spiral occurs at a frequency about twice that for the two-arm spiral, yet the gain decrease with the elevation angle is about the same as for the two-arm spiral.

2.2.4 Summary of Results

From study of the experimental results on microstrip spirals, we can draw the following conclusions:

- Gain consistently increases with increasing antenna-to-ground plane spacing.
    - This principle fails near $\lambda/2$ spacing.
    - Adequate spacing is well within requirement (~12").
- Gain is nearly constant for λ smaller than Circumference · Mode number (C · M).
- Peak gain drops through 0 dBi when $\lambda \approx 1.3$ C · M.
- Peak gain drops below -15 dBi for $\lambda \approx 2$ C · M.
- In the undersized antenna region, gain drops ~18 dB per octave for Mode 2, ~25 dB per octave for Mode 1.
- Use of absorber cuts the gain level slightly for $\lambda \geq C$.
- Use of absorber reduces the gain ripple for $\lambda \leq C$.
- Absorber effect is generally positive; placement and amount needs optimization.
- For same gain in the undersized antenna region, Mode 2 antenna must be twice as large or have twice the material, relative to a Mode 1 antenna.

- Mode 1 gain is a smoother function of frequency than Mode 2 gain (may depend primarily on feed network).
- The feed network is more complicated for Mode 2 (more errors, more cost).

Results show that Mode 1 is the preferred mode of operation. With the Mode 1 microstrip as studied herein, size and gain requirements can probably be satisfied down to a frequency of about 60 MHz. As discussed in the following subsection, the lower frequency limit can possibly be decreased through the use of a ferrite substrate material.

2.2.5 Use of Special Substrate Materials

The lower frequency range of operation of a microstrip spiral antenna of a given size can be reduced through the use of ferrite materials. Some guidelines for applications of this type of material include:

- Must use superstrate material similar to substrate,
- Materials must have nearly equal relative permittivity and permeability,
- Do not use materials with larger permittivity and permeability than required, and
- The materials must be low loss.

Results of this approach will be:

- Size reduction for a given frequency of operation will be a factor about equal to the geometric mean of the permittivity and permeability,
- Beam will broaden toward the horizon, and
- Gain will be degraded.

To illustrate the effect of using such material, consider the examples defined by table 2-1.

Table 2-1. Estimated Microstrip Spiral Performance with Ferrite Materials

ϵ_r, μ_r	Size, dia.	Mode	Lowest Freq.	Peak Gain
4	50"	1	20 MHz	-1 dBi
8	50"	2	20 MHz	-5 dBi

These performance estimates are based on the use of a Lithium Ferrite. In a powdered form, this material has a specific gravity of about 1. The resulting weight of a 50-inch diameter cylinder, five inches deep, would be about 340 lbs. This form of material would be appropriate for the Mode 1 example given in table 2-1. To obtain the Mode 2 characteristics, pressed material would be required, and result in a significantly higher weight.

2.3 DISKCONE ANTENNAS

Beyond the investigations of loop and microstrip antennas, the next series of antenna investigations centered on a class of antennas which consist of a body of revolution (BOR) in the azimuth plane to provide an omni-directional azimuth pattern. Antennas which fit this description include monopole and diskcone antennas and variants thereof. Three examples which will be further discussed will be the diskcone, the conical monopole, and the Goubau antenna.

The diskcone antenna, as the name implies, consists of a disk for the top of the antenna, and a cone whose apex approaches the diameter of the outer conductor of the coax used to excite the antenna. The center conductor of the coax terminates at the center of the disk, which is mounted perpendicular to the axis of the cone and coaxial transmission line. This antenna is designed for vertical polarization, and it has a radiation pattern basically equivalent to a dipole. The pattern may be represented by a solid of revolution generated by a rotating figure eight. The peak of the beam is on the horizon, and the nulls are at

zenith and at 180 degrees from zenith. The uniqueness of this antenna is it's broadband performance characteristics and simple design. One of the first references to this antenna is the IRE Proceedings article by Armig G. Kandoian [15].

In general, the impedance and pattern variations of the diskcone antenna, as a function of frequency, are less severe than those of a dipole of fixed length. The E field is excited vertically between the disk and the cone, and the major axis of the antenna pattern is on the horizon. The gain of this antenna is equivalent to a dipole, 2.14 dBi. The performance of this antenna is electrically equivalent to a high pass filter with its associated low-frequency cutoff. Below the design or cutoff frequency, the antenna is inefficient, and a large VSWR exists on the transmission line attached to the antenna. The cutoff frequency is based on the dimensions of the antenna, primarily the slant length of the cone. This cutoff frequency occurs where the slant length of the cone is approximately $\lambda/4$. The operating bandwidth of this antenna is typically one octave or more; however, antennas operating over bandwidths of approximately 600% are feasible.

The diskcone antenna is used extensively in the UHF and some VHF communication bands for both commercial and military applications. This antenna is typically mounted on a mast, elevated above a ground plane. One concern when using this antenna for the current requirements is the performance of the antenna when operating on or near a ground plane. Return loss measurements and pattern measurements were performed to evaluate antenna performance when adjacent to a ground plane.

Variations of this antenna have been made to simplify the construction methods. To reduce the weight and wind resistance of the antenna, the solid conical skirt has been replaced with radial elements of the same slant length. These antennas have been observed to operate with as few as 4 radial elements spaced 90° apart. This small number of radial elements may be sufficient when the antenna is elevated significantly above a ground plane.

However, in the vicinity of a ground plane, the number of elements can significantly impact the return loss of the antenna.

When radial elements are used to construct the conical skirt, the number of elements used were found to be critical when the antenna is located in close proximity to a ground plane. Figure 2-22 shows measured return loss of a diskcone antenna placed on a ground plane. The antenna, as originally constructed, used 12 radials for the conical skirt. The number of radials used during the return loss measurement were reduced from 12 to 6 and finally 3. The data show that with 6 or more radials, performance was minimally impacted. However, as the number was reduced to 3, it was noticed that more energy was leaking through the conical skirt, reflecting off the ground plane, and reflecting back into the coaxial gap. A beat frequency of 430 MHz was observed, which corresponds to reflection points spaced approximately 13.6" apart, and which is comparable to the disk-to-ground plane spacing of the antenna under test.

For the following discussions concerning diskcone antennas, data were measured using the antenna illustrated in figure 2-23.

Beyond the impact of the number of radials composing the conical skirt as mentioned earlier, the antenna when placed directly upon a ground plane has a different return loss than in free space. This is illustrated in figure 2-24. In this measurement, the forementioned antenna was placed atop a 28" square aluminum plate to replicate the ground plane. The first trace illustrates the 2.0:1 VSWR bandwidth ranging from 220 MHz to 400 MHz when the antenna is operated without a ground plane. Once the antenna is placed on the ground plane, the previous band is inoperable, and the new band is approximately 420 to 580 MHz. Apparently energy near the base of the cone has not been sufficiently radiated or attenuated to prevent the interaction of the antenna with the ground plane. The next investigation was to quantify the proximity effect of the ground plane. In this test, as shown in figure 2-25, the antenna was elevated until the desired performance

was restored. In this figure, the first trace is for the antenna on the ground plane, the second trace is for the antenna elevated 1" above the ground plane, and the last trace is for the antenna elevated 2" above the ground plane. Once the antenna is elevated above the ground plane approximately 2", the ground plane interaction is negligible. Except for a few extrusions above 10 dB, the 2.0:1 VSWR bandwidth is 220 - 580 MHz, approximately 260%.

With the acceptable performance established with the return loss measurements, the next concern was the radiation patterns. A mast type mount was constructed to allow measurement of the antenna on a far-field range. It was impossible to eliminate the interaction of the antenna with the mount, but precautions were made to minimize this interaction, especially when making the elevation measurements. To minimize interactions with the ground when making elevation pattern measurements, the antenna was rotated 90 degrees, and the elevation patterns were measured in the plane of the azimuth positioner. The difficulty of measuring this antenna arises from the cone of energy radiating from the area between the cone and the disk, which is present at all azimuth angles and easily interacts with any adjacent reflective surface.

Elevation patterns were measured at 185, 250 and 400 MHz with four different ground plane confiigurations, as follows: no ground plane present, the ground plane placed at the end of the conical radials, the conical radials spaced 3" from the ground plane, and the conical radials spaced 6" from the ground plane. In all cases, the ground plane was the 28" square aluminum plate previously mentioned. The pattern performance was not as smooth as desired, but this can possibly be attributed to range effects, and the frequencies chosen. Due to crowding of the VHF and UHF spectrum, frequencies with minimal interference were chosen for pattern measurements. The lowest test frequency was very close to the cutoff frequency and could possibly explain the pattern irregularity. The primary goal was to establish the interaction of the ground plane with the antenna patterns. At the lower frequencies, the impact of the ground plane was minimal; however, as the

frequency of operation exceeds one octave, the elevation patterns are affected more by the proximity of the ground plane.

The azimuth patterns were measured with the ground plane adjacent to the radials. The azimuth patterns were measured at 185, 250,400, 500, 625, and 740 MHz. The patterns were within 2 dB of being omni directional except at 185 MHz (3 dB), 500 MHz (2.8 dB) and 740 MHz (2.6 dB). The lowest frequency behavior once again could be related to the proximity to the cutoff frequency.

From the measured data, the diskcone antenna performance is acceptable within the first octave bandwidth when slightly elevated above a ground plane. The skirt can consist of radials, or a continuous metal skirt. Figure 2-26 provides design dimensions for antennas to operate from band C to band F. If the diskcone antenna is chosen to operate in any band other than F, low pass filters should be incorporated to attenuate the higher frequency responses, thereby improving adjacent band isolation between antennas. For example, if an antenna is designed to operate in band C, the dimensions of the antenna would be chosen to operate at frequencies above 80 MHz, and a low pass filter would be placed in series with the antenna to attenuate frequencies above 160 MHz.

2.4 CONICAL MONOPOLES

Of all the antennas discussed, the conical or thick monopole seems to be the best candidate based on design simplicity, but its radiation pattern could be a limitation. The uniqueness of this antenna is that the ground plane of the mounting platform can be naturally integrated as the ground plane of the antenna, and the monopole could penetrate the ground plane with the radiating element located above the ground plane. Many references exist considering monopole antennas, including Johnson [16], Schelkunoff [17], and Baker and Botha [18]. The last reference is very applicable to the current applications.

A typical λ/4 monopole utilizes a small diameter radiating element above a ground plane, and typically the performance of the antenna is narrow-banded. If the thickness of the radiating element is increased while maintaining the same length, the frequency range can be increased. For example, the operating bandwidth of the antenna can be increased upwards to 300%, with the lowest frequency based on the height of the antenna being at least λ/4. The increase in thickness of the radiating element can vary from the use of a cylinder for a radiating element, to a cone or conical shape. Critical to the performance of the antenna is the compensation of the gap capacitance between the radiating element and the end of the coax used to excite the element. The article by Baker and Botha presents antenna performance for various length-to-diameter ratios of the radiating element and for a conical radiator.

For initial test purposes, a scaled version of the conical monopole was fabricated. A section of 0.141" semi rigid coax was used as the transmission line and, a conical radiating element was machined to a height of 0.40", with an apex approximately 0.075" and a maximum diameter of 0.530" with a ground plane of 2" diameter. Figure 2-27 presents the return loss of this antenna. With this design, the lowest frequency should be 7.38 GHz. The measured 10 dB return loss (or 2.0:1 VSWR) bandwidth was 5.84 to 18 GHz, better than 300%. Antenna pattern measurements were not made due to time restraints. However, sufficient data are found in the reference by Baker and Botha to provide elevation pattern information. In this document, pattern data are presented for a conical monopole at 2, 4 and 10 GHz. The primary concern for this antenna is the elevation pattern. The elevation peak of the antenna pattern typically varies from 40 degrees at the lowest frequency to 70 degrees at the upper frequency. Over the first octave, the peak of the beam appears to remain consistently at 40 degrees above the horizon; however, the roll-off of the antenna pattern is approximately 3 dB at the horizon as shown in figure 2-28. With this antenna design, the antenna gain at the horizon, assuming a peak gain of 2.14 dB, would be approximately -0.86 dB at the horizon. This could be unacceptable for bands D,E and F but should warrant further consideration for band C.

2.5 GOUBAU ANTENNA

The Goubau antenna [19] is a unique antenna which is named after its inventor, Dr. George Goubau. Figure 2-29 is an illustration of the Goubau antenna. The antenna has a very low profile, and it has been postulated to perform over an octave bandwidth. The antenna is a complex structure which could be described as a top-loaded folded monopole. Due to Dr. Goubau's death in 1980, very little information can be found regarding this antenna. Based on very limited details on the height of the antenna and the diameter of the top disc, along with the illustration of figure 2-29, a test article of the Goubau antenna was fabricated. Initial performance of the antenna is poor in regards to bandwidth, as shown in figure 2-30. The performance could be related to the dimensions chosen for the antenna, but further investigations of this antenna would require significant modeling of the antenna using a method-of-moments program to finalize dimensions. To allow further investigations of the diskcone and conical monopole antennas, further modeling of the Goubau antenna at this time was not possible.

Dimensions which can be changed to affect the performance of the antenna include: diameter and spacing of support posts, including grounded and driven elements, diameter of the inductive loop along with the post spacing, and diameter and segmentation of the capacitive disk atop the antenna.

Future investigations of this antenna would include method-of-moments modeling to determine:

1. The effect on the lower frequency of operation of changing the capacitive disk on top and of changing the diameter of the inductive loop while changing the post spacing.

2. The effect of changing the height, diameter and spacing of the posts used to support the inductive loop.

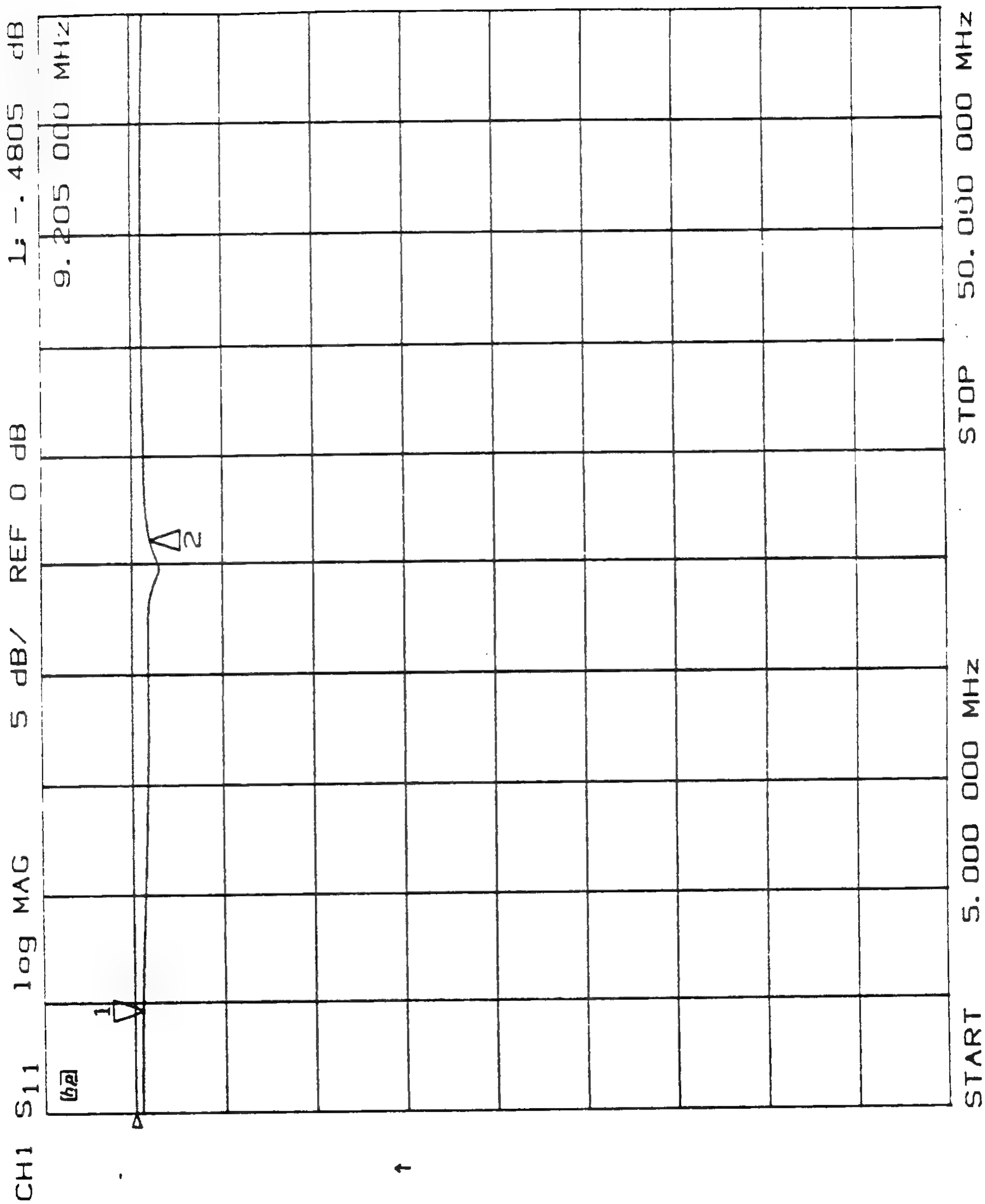


Figure 2-1. Return loss measurement for IsoLoop antenna adjacent to a ground plane.

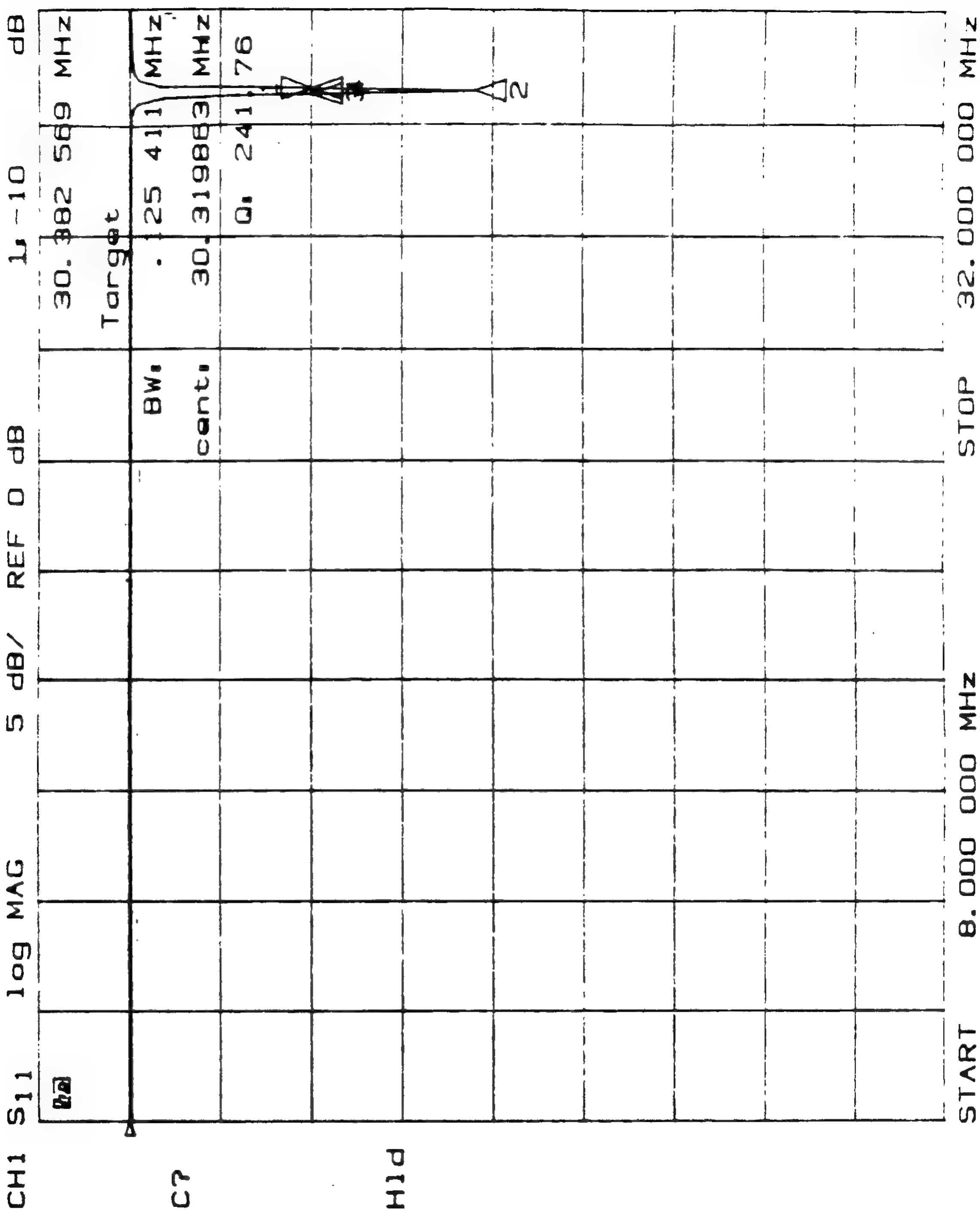


Figure 2-2. Return loss measurement for IsoLoop antenna elevated 60" relative to a ground plane.

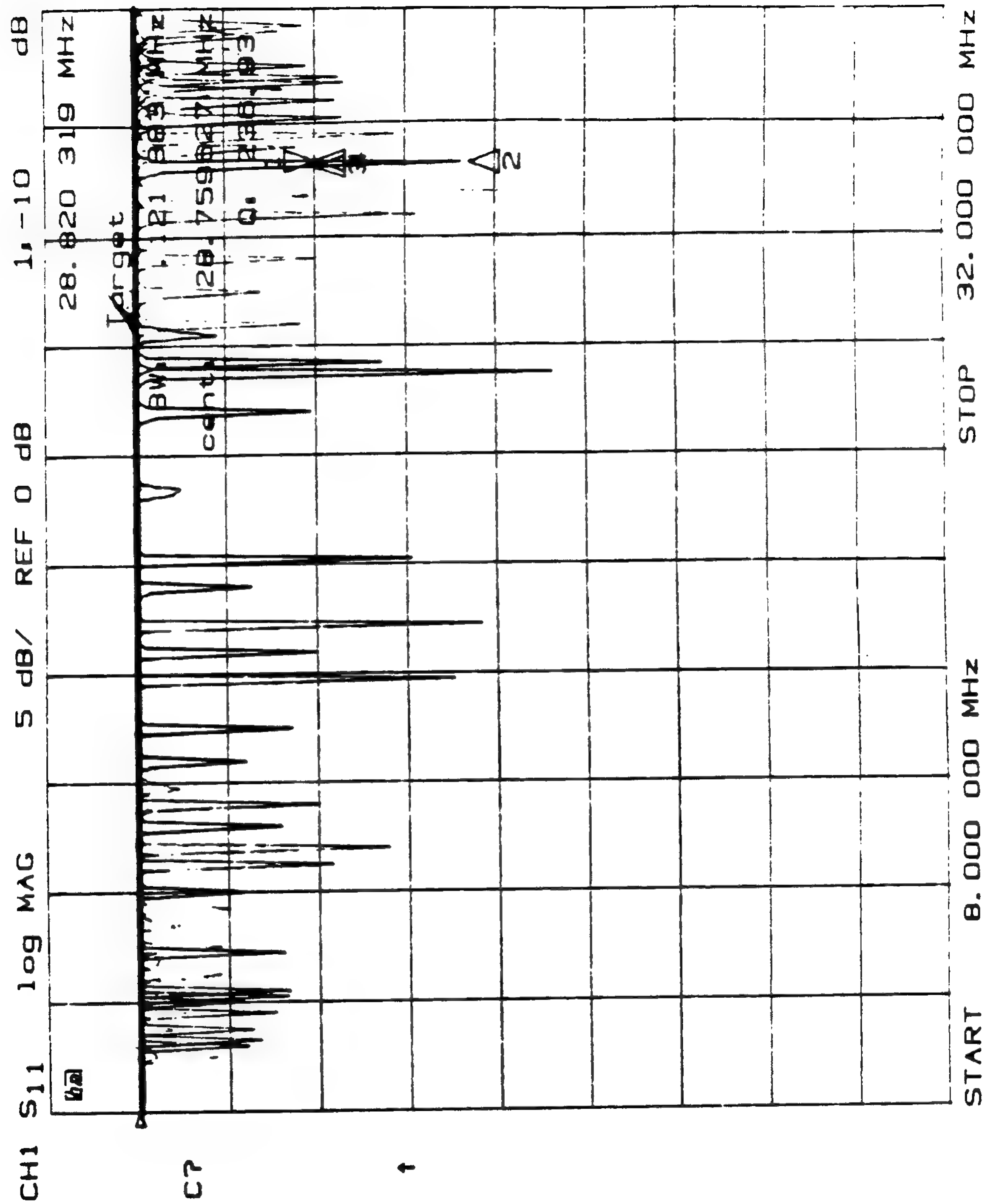


Figure 2-3. Return loss measurements for IsoLoop antenna elevated above a ground plane while tuning the antenna for different frequencies.

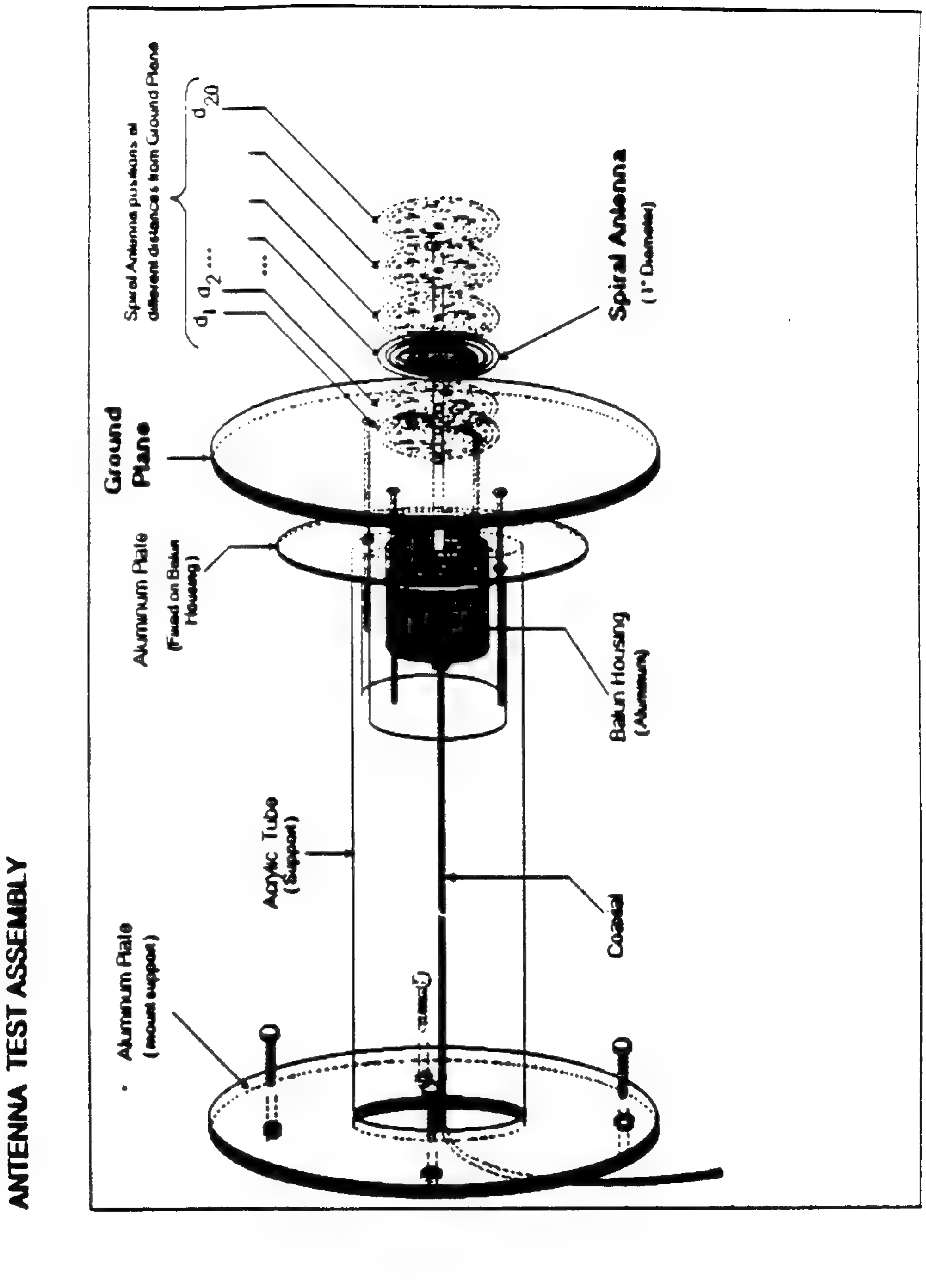


Figure 2-4. Experimental set-up for two-arm spiral.

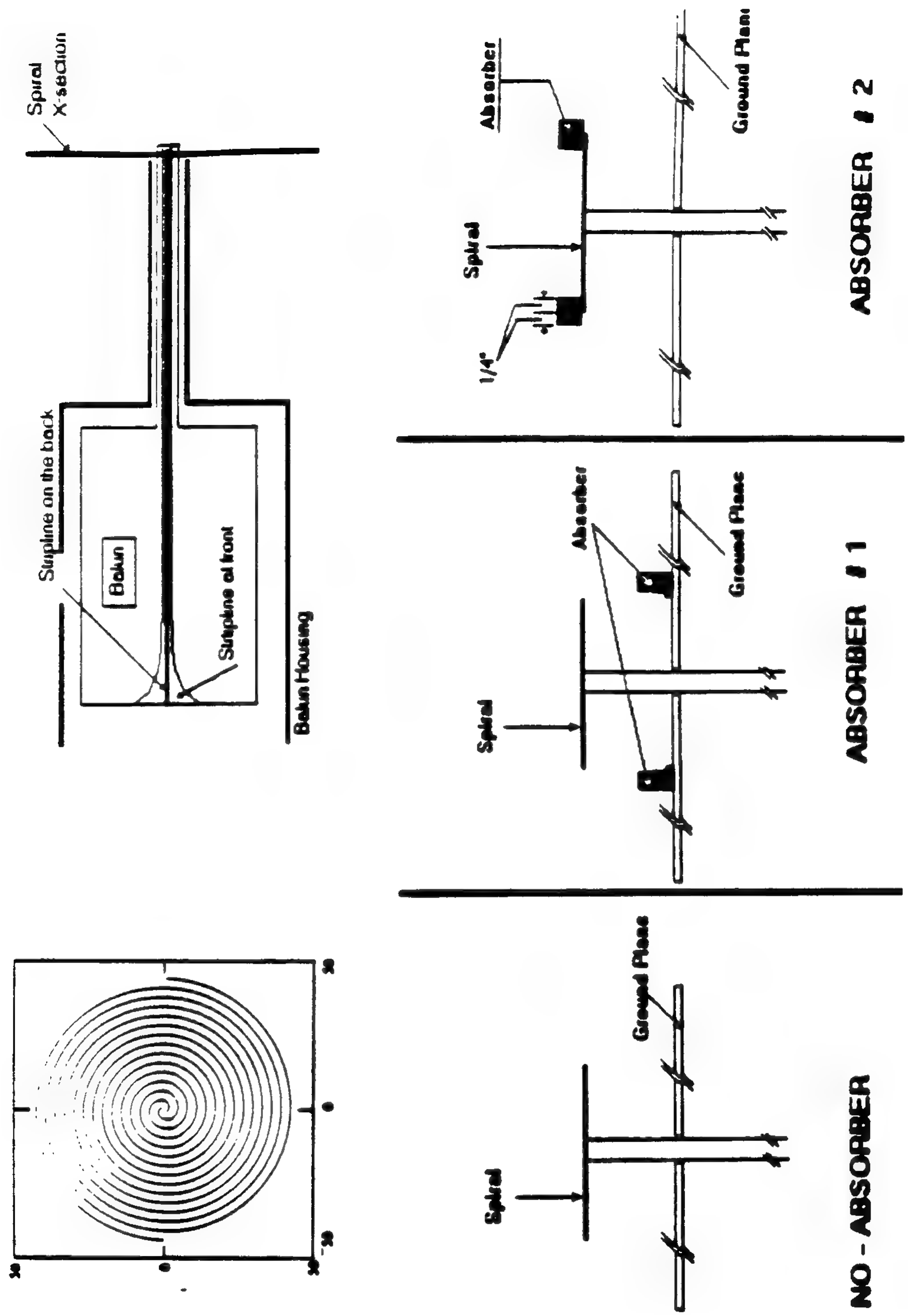


Figure 2-5. Method of feeding two-arm spiral and placement of absorber.

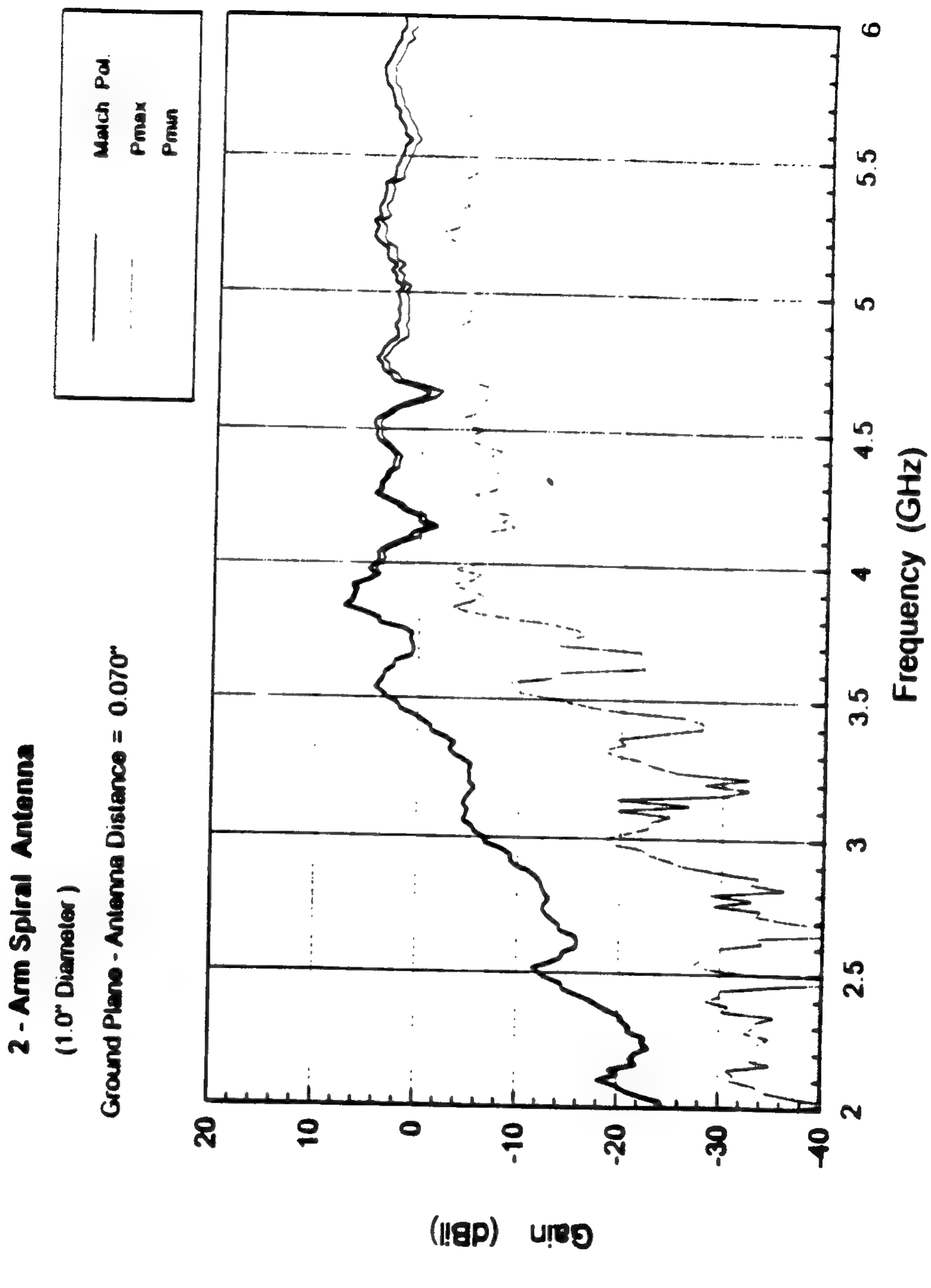


Figure 2-6. Measured peak gain versus frequency for a two-arm spiral without absorber and a ground plane spacing of 0.070 inch.

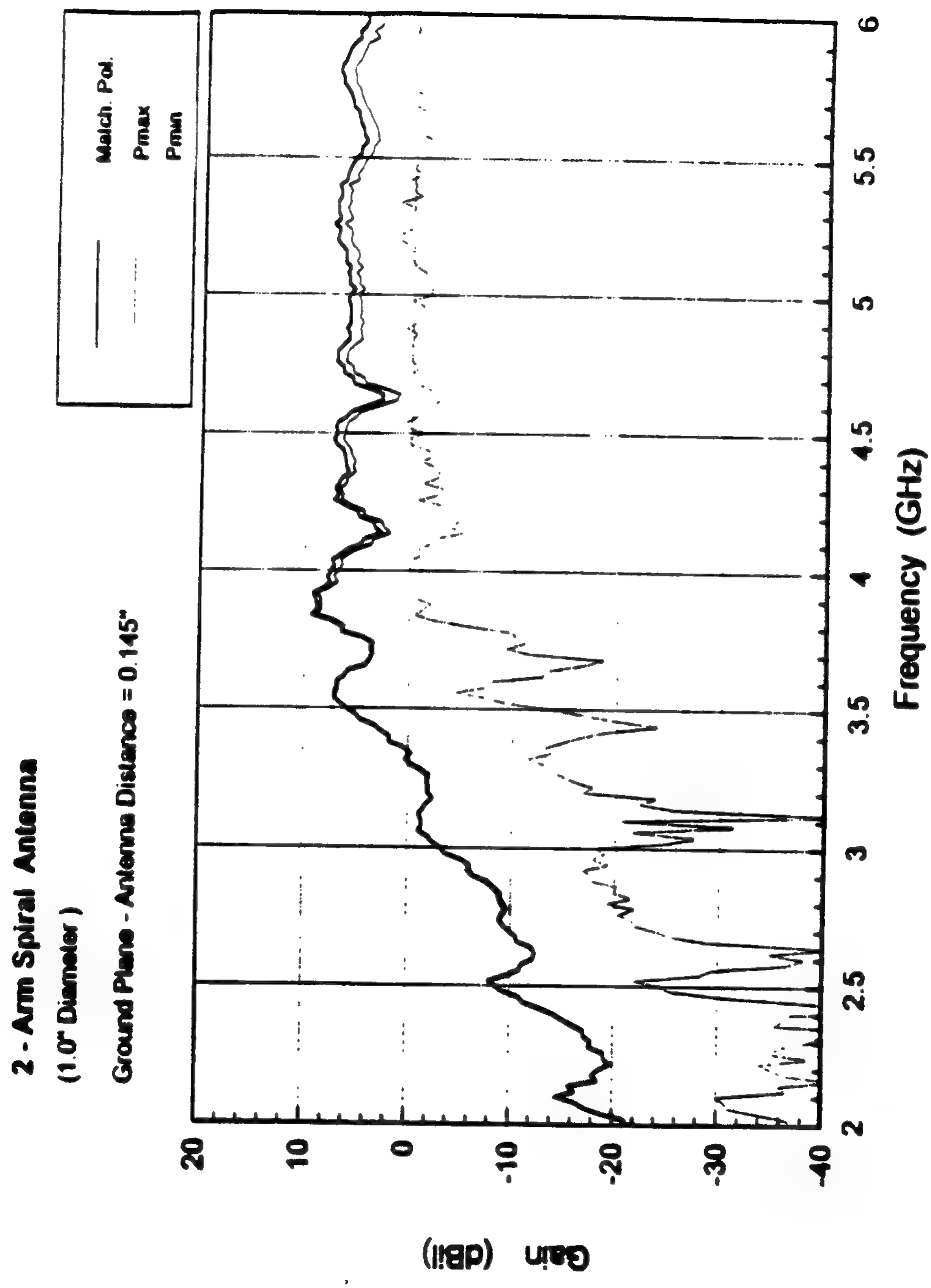


Figure 2-7. Measured peak gain versus frequency for a two-arm spiral without absorber and a ground plane spacing of 0.145 inch.

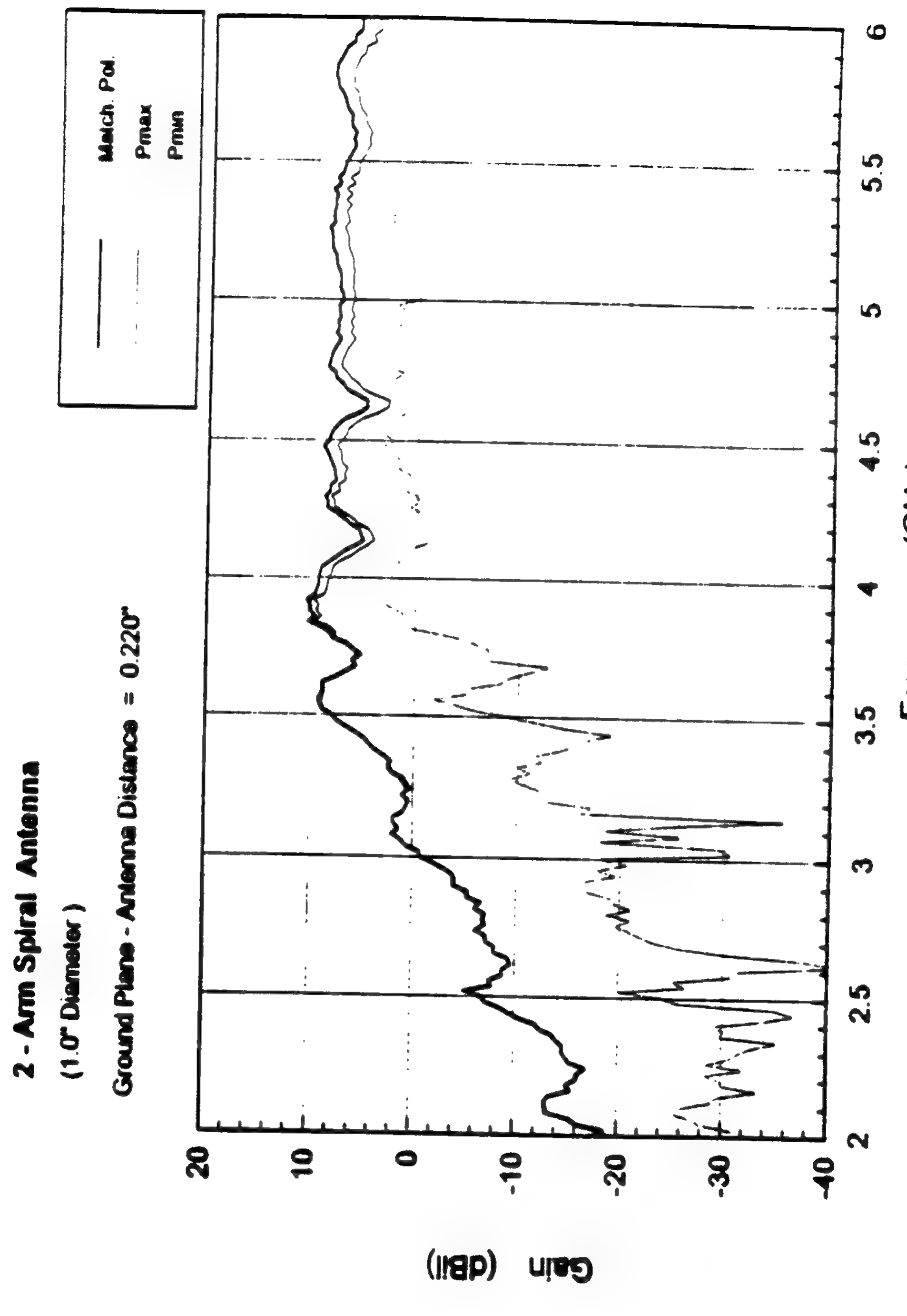


Figure 2-8. Measured peak gain versus frequency for a two-arm spiral without absorber and a ground plane spacing of 0.220 inch.

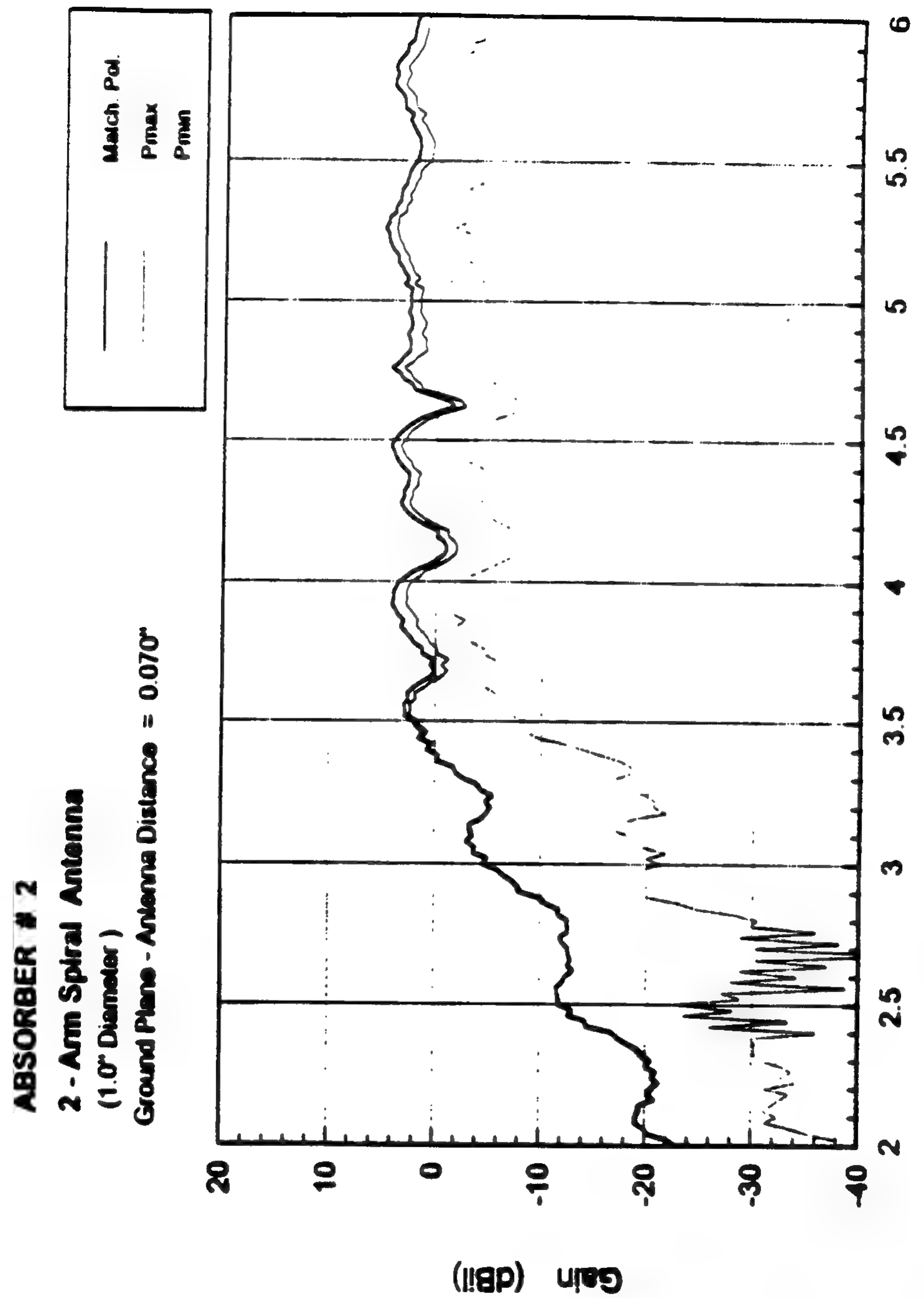


Figure 2-9. Measured peak gain versus frequency for a two-arm spiral with absorber and a ground plane spacing of 0.070 inch.

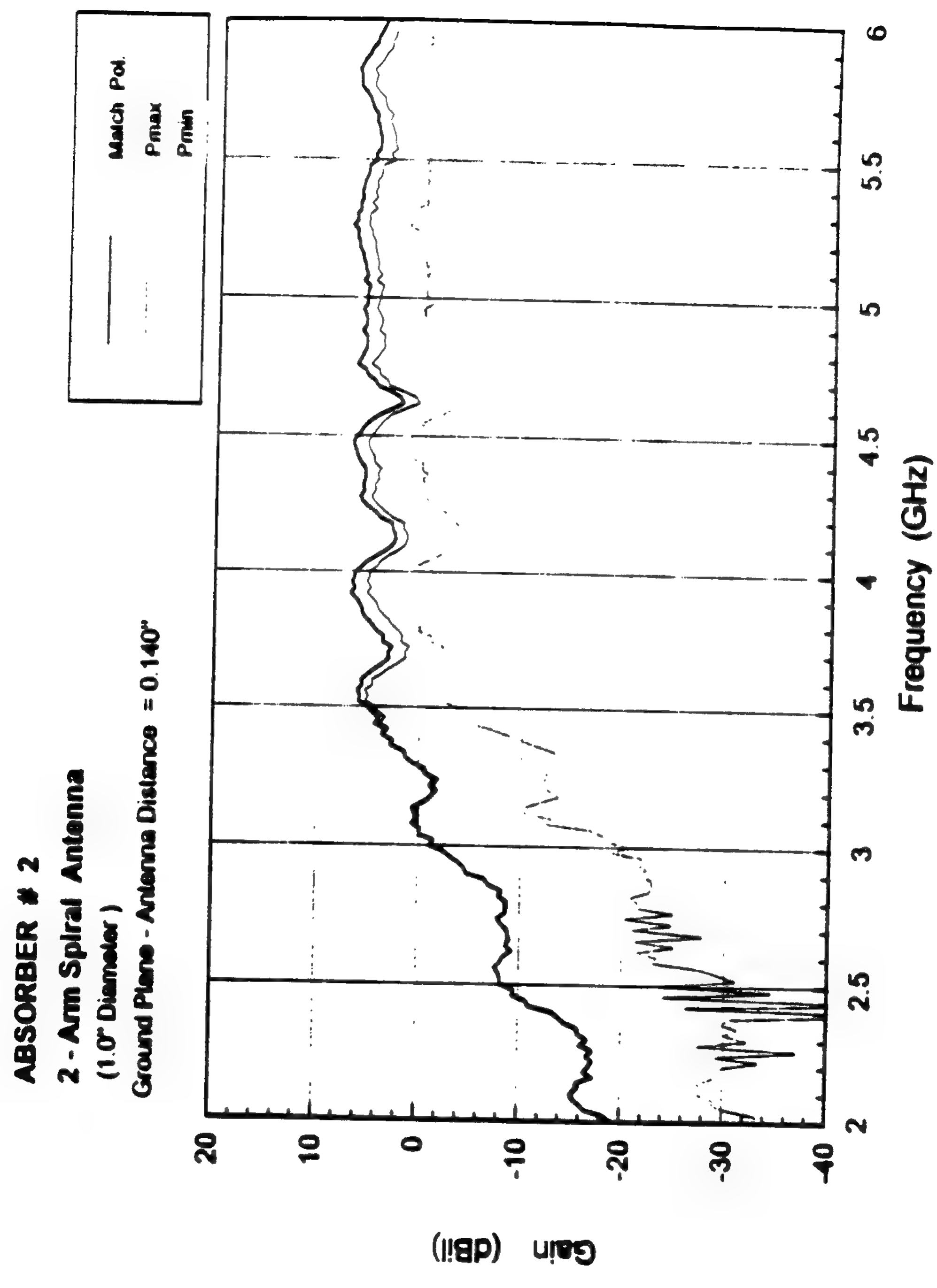


Figure 2-10. Measured peak gain versus frequency for a two-arm spiral with absorber and a ground plane spacing of 0.140 inch.

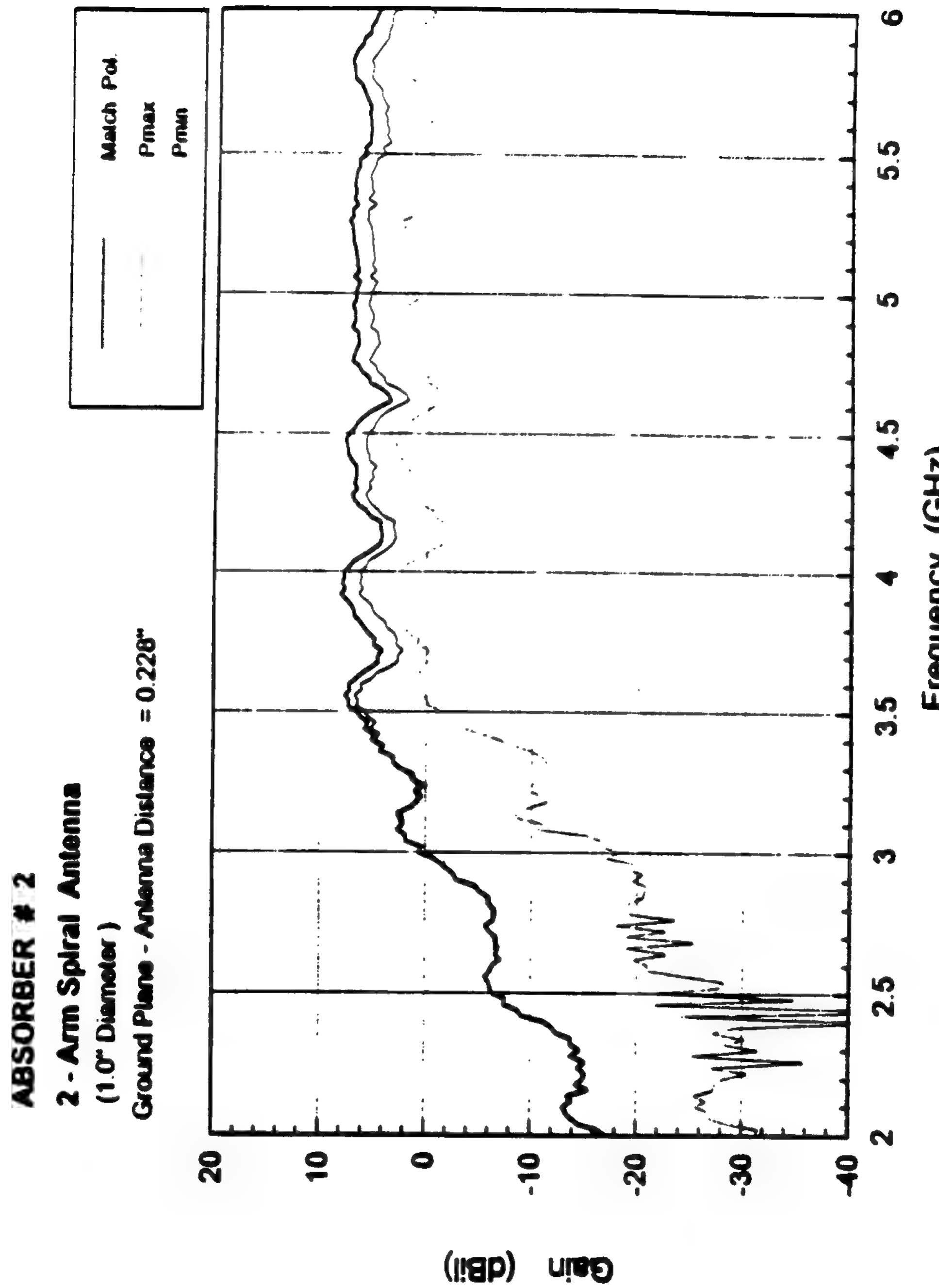


Figure 2-11. Measured peak gain versus frequency for a two-arm spiral with absorber and a ground plane spacing of 0.228 inch.

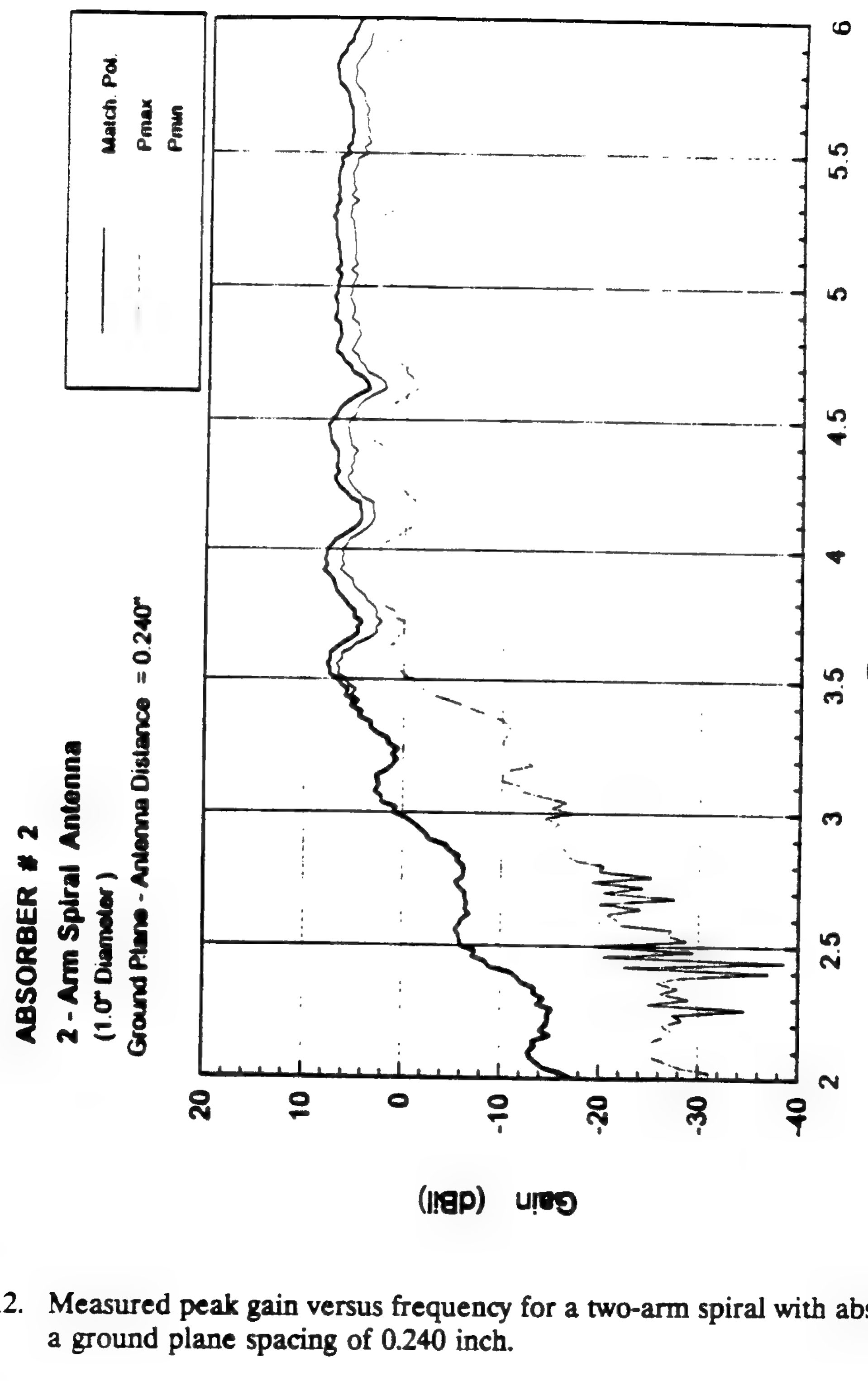


Figure 2-12. Measured peak gain versus frequency for a two-arm spiral with absorber and a ground plane spacing of 0.240 inch.

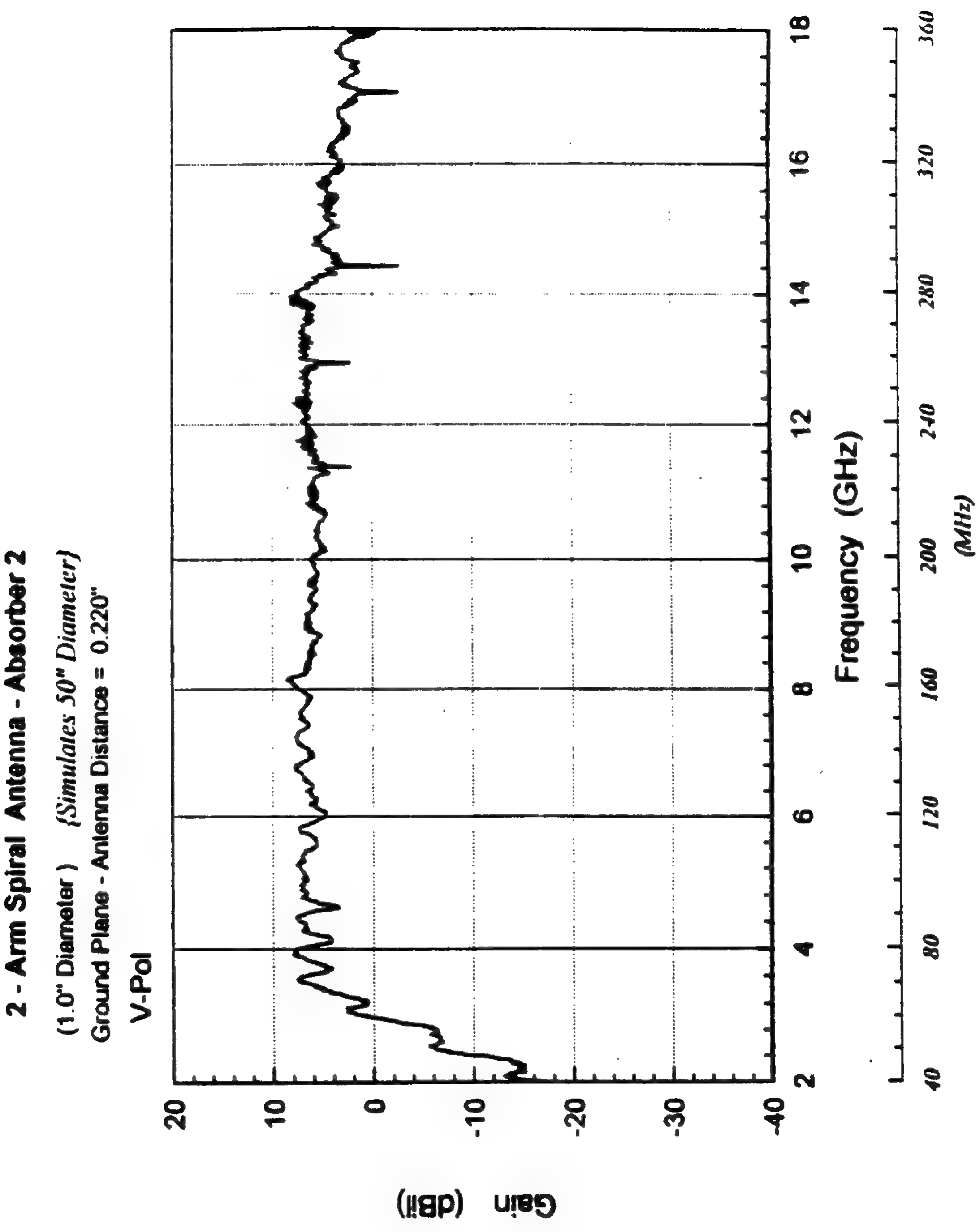


Figure 2-13. Gain versus scaled and actual frequency for a two-arm spiral with absorber and vertical polarization.

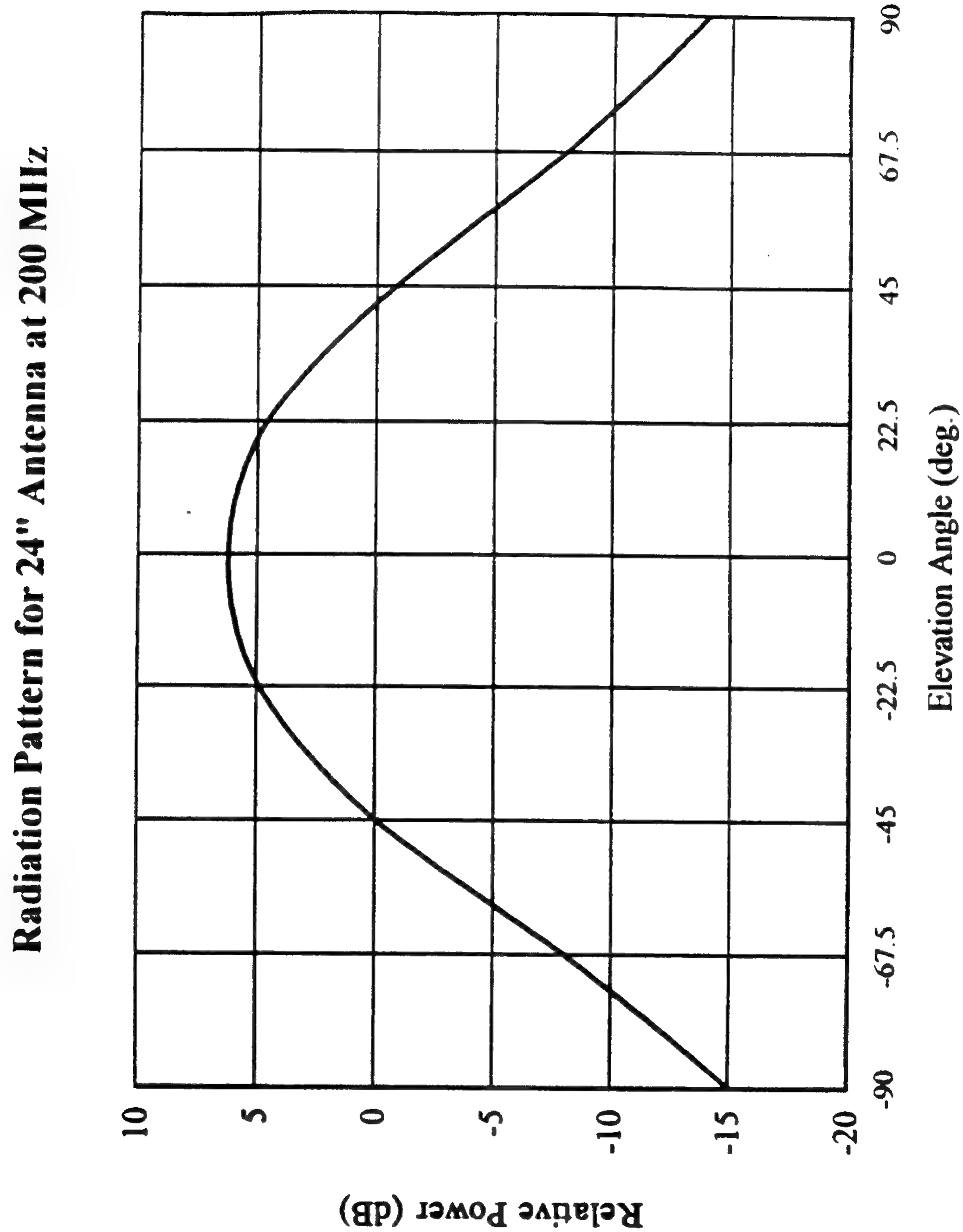


Figure 2-14. Gain versus elevation angle for un-optimized two-arm spiral antenna.

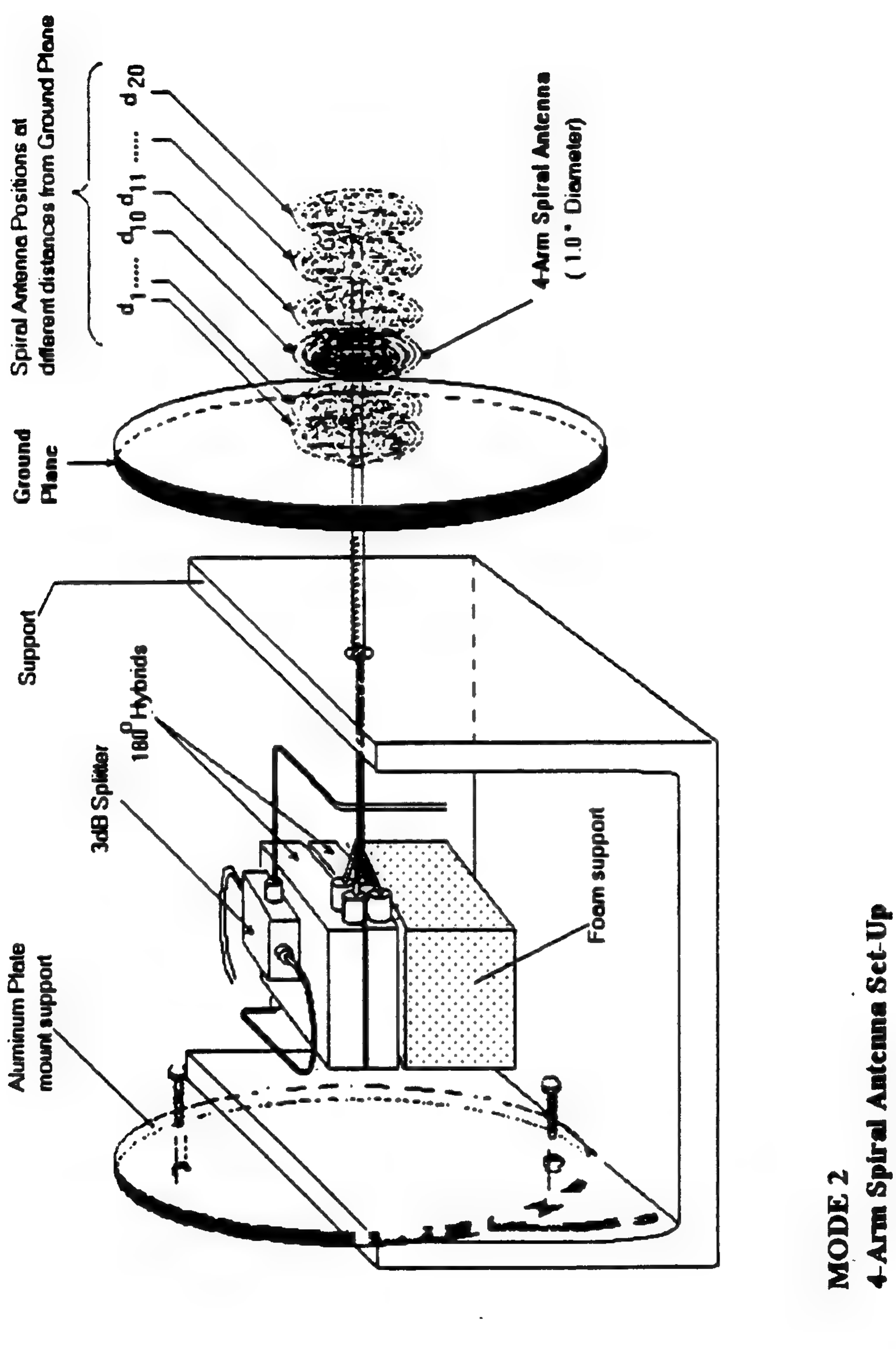


Figure 2-15. Experimental set-up for four-arm spiral.

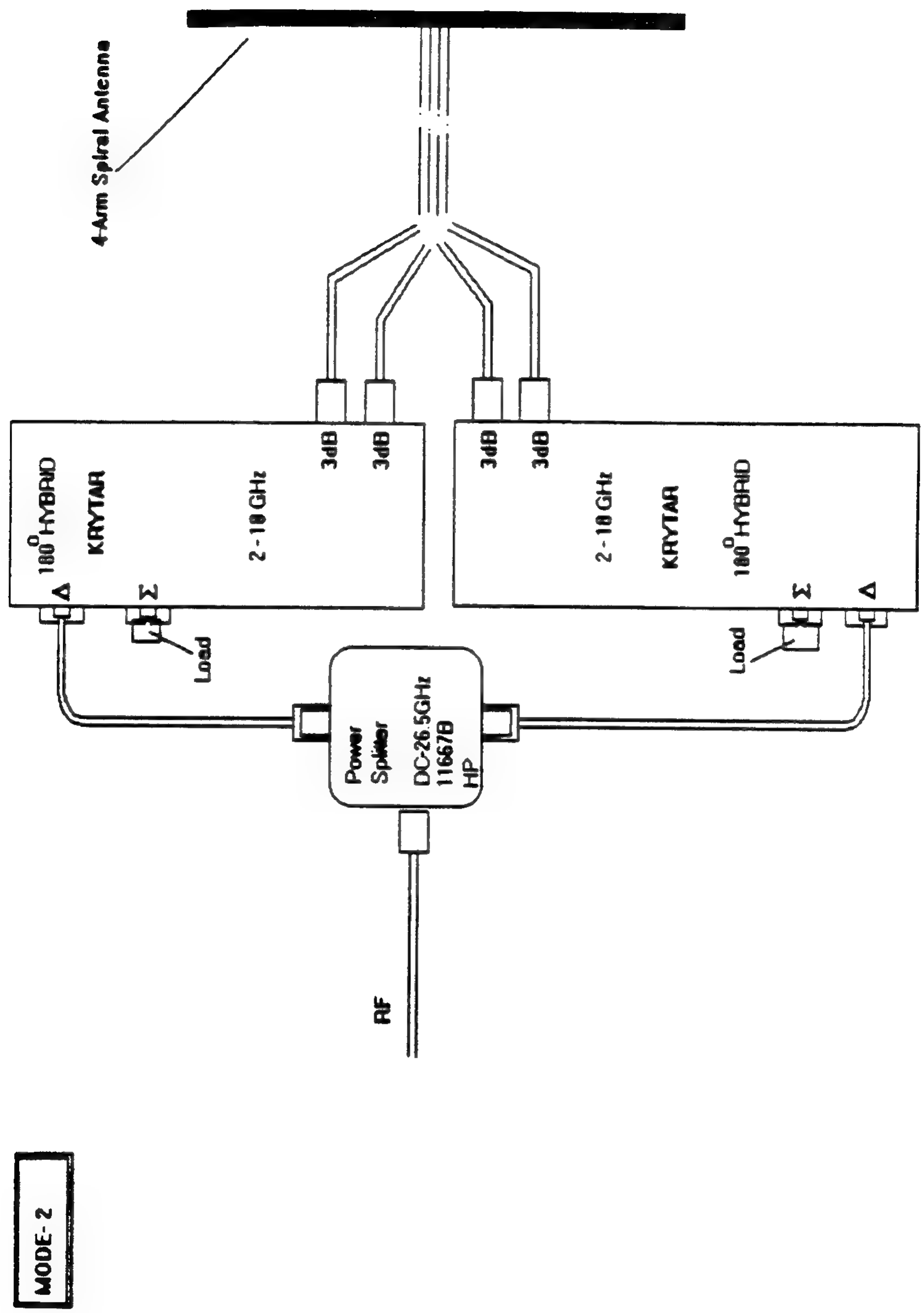


Figure 2-16. Method of feeding four-arm spiral.

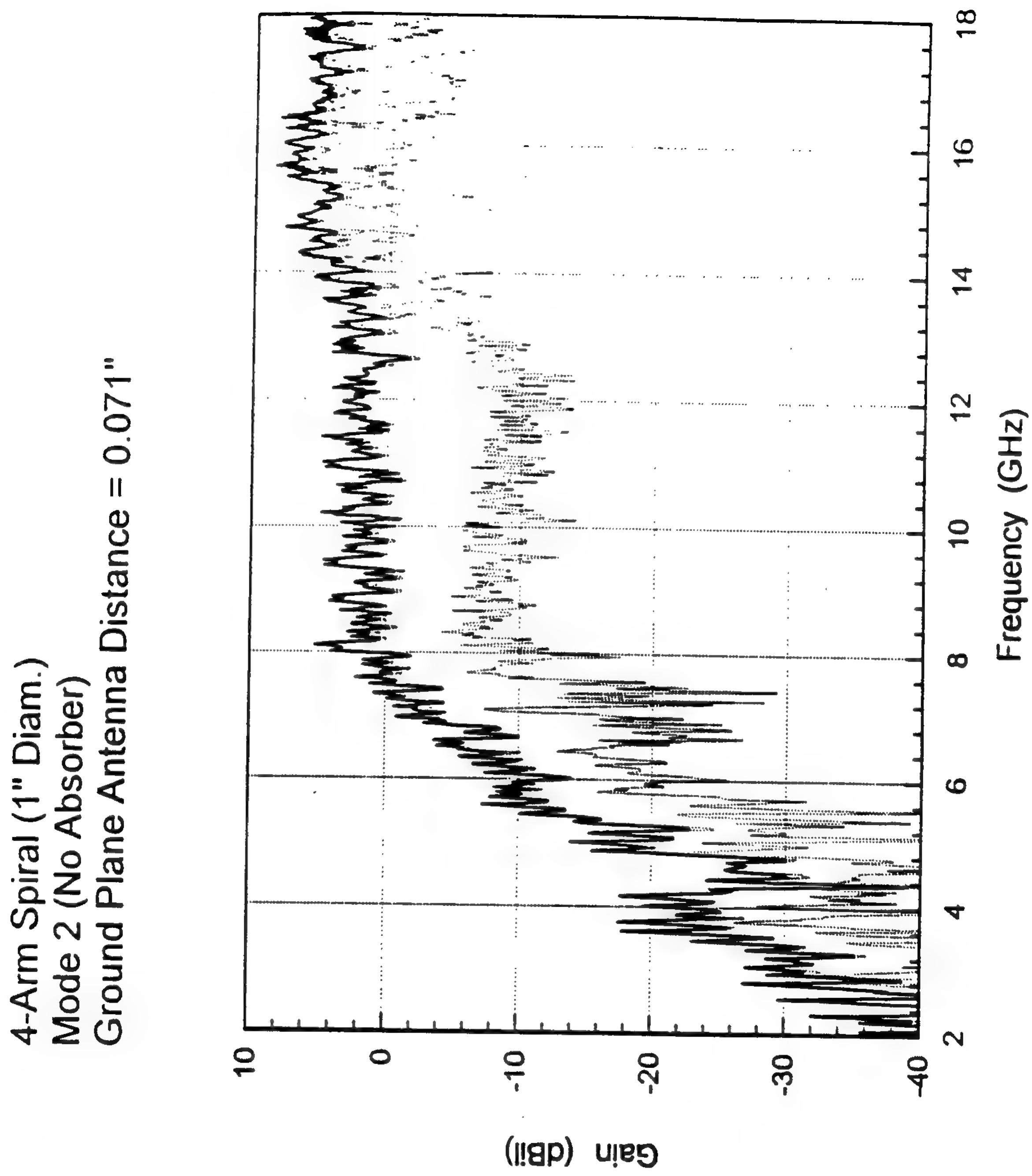


Figure 2-17. Measured gain versus frequency for a four-arm spiral with a ground plane spacing of 0.071 inch and no absorber present.

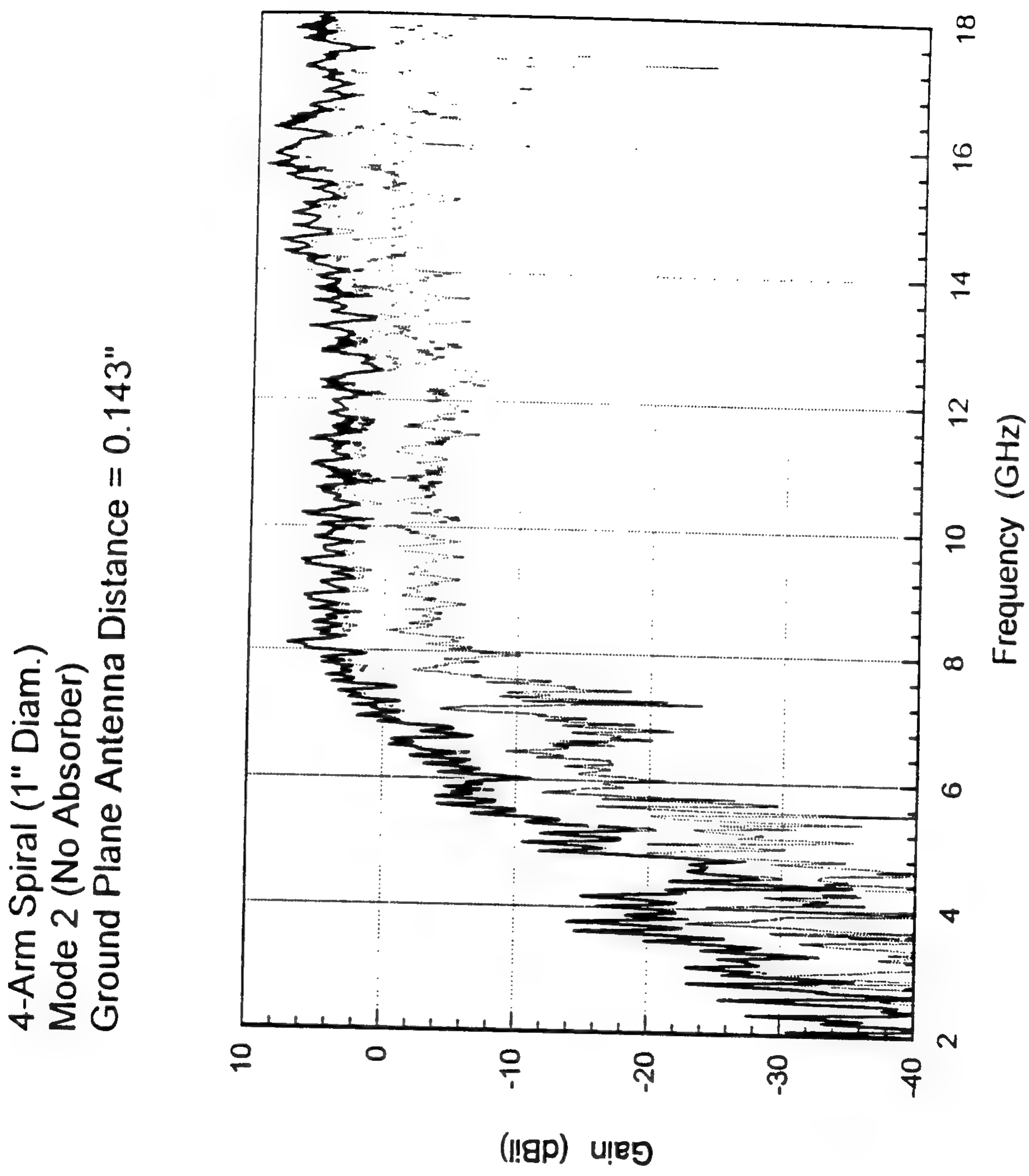


Figure 2-18. Measured gain versus frequency for a four-arm spiral with a ground plane spacing of 0.143 inch and no absorber present.

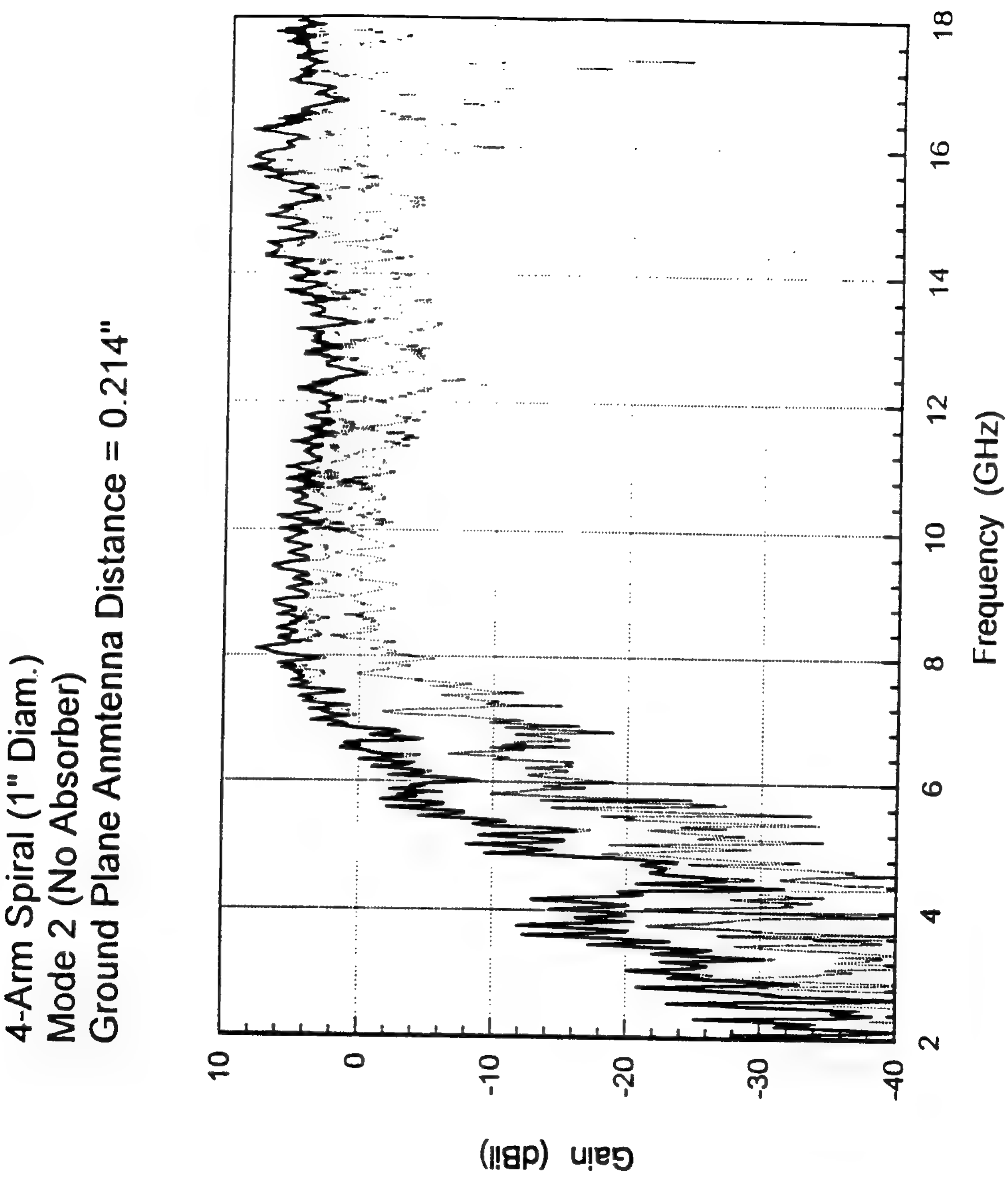


Figure 2-19. Measured gain versus frequency for a four-arm spiral with a ground plane spacing of 0.214 inch and no absorber present.

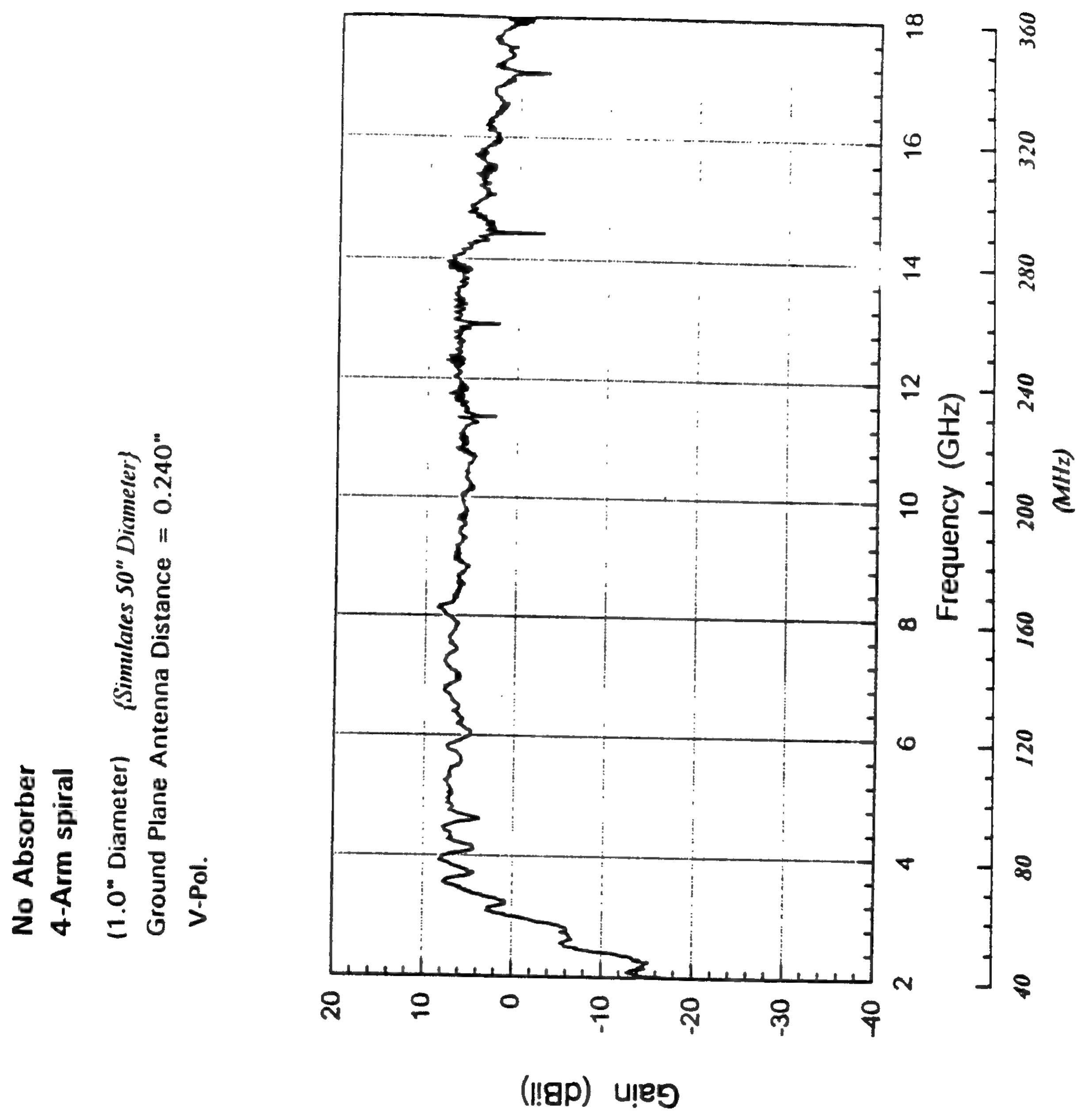


Figure 2-20. Measured gain versus frequency with vertical polarization for a four-arm spiral with a ground plane spacing of 0.240 inch and no absorber present.

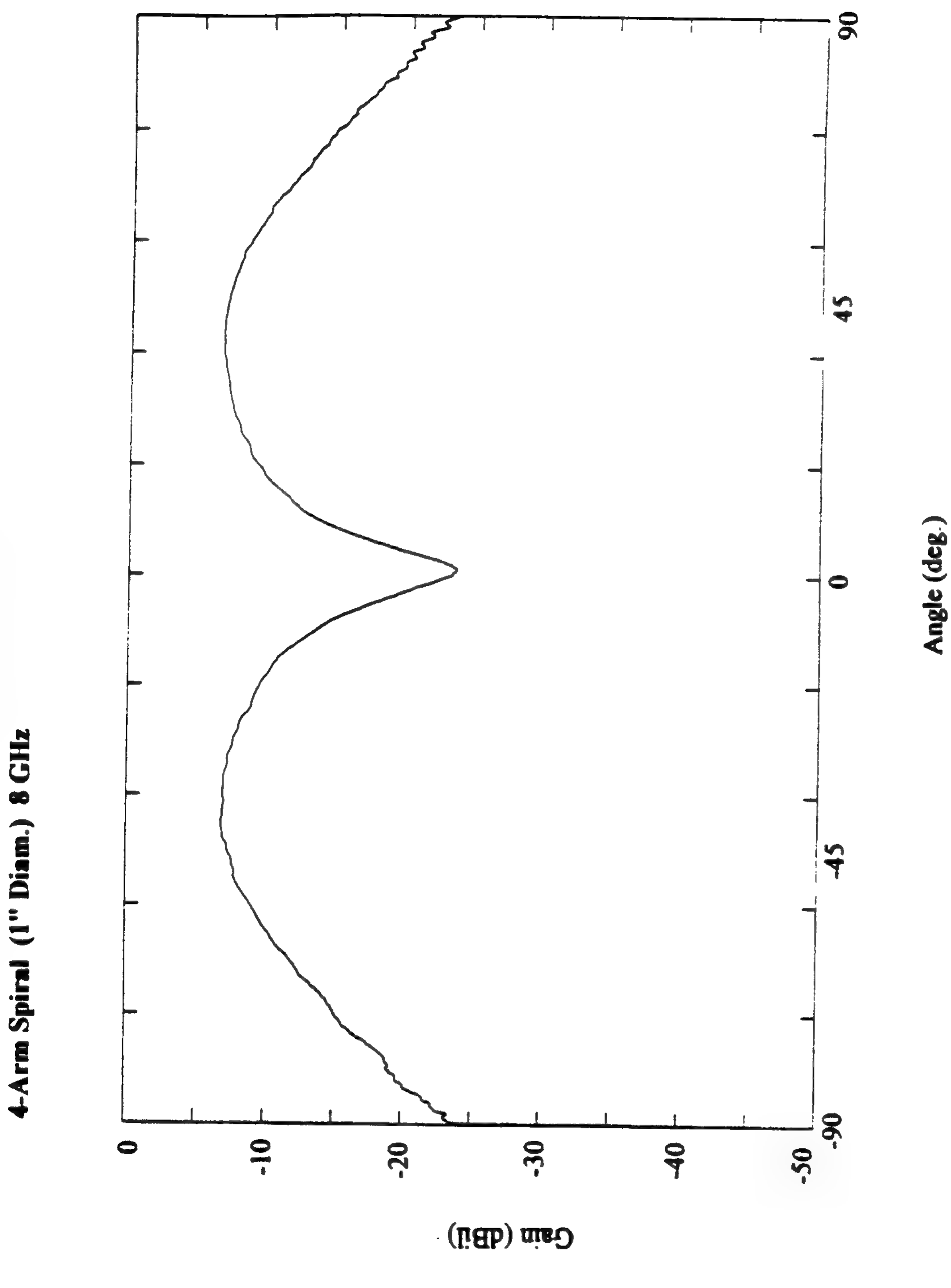


Figure 2-21. Gain versus elevation angle for four-arm spiral at 8 GHz.

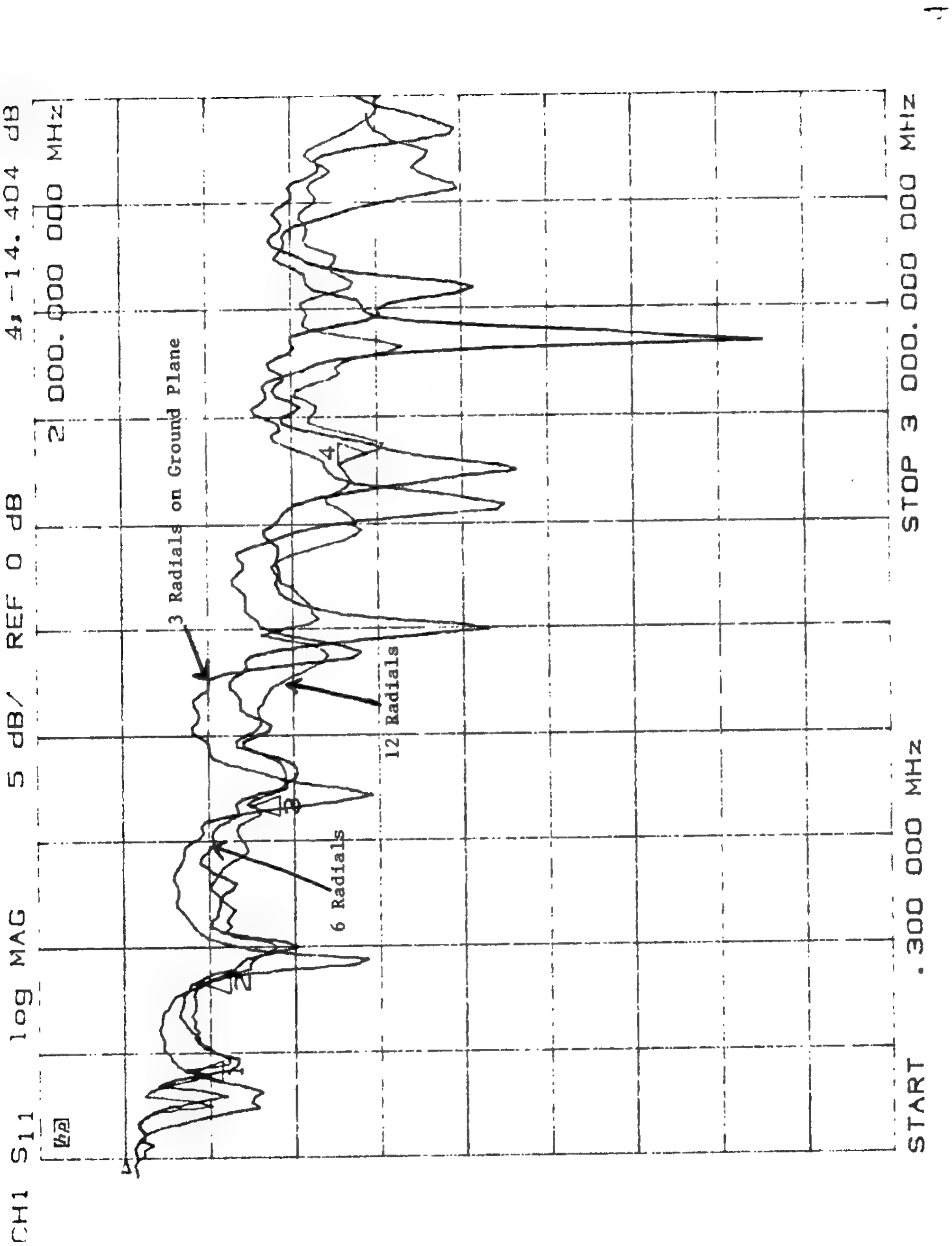
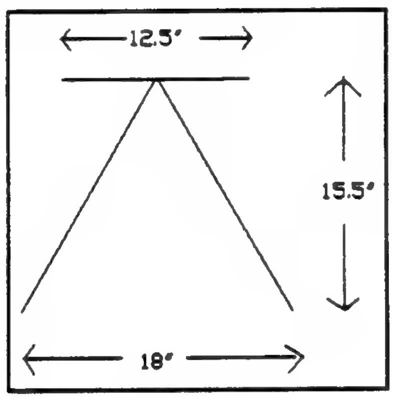


Figure 2-22. Return loss of diskcone antenna with and without ground plane.

ANTENNA, UHF DISC-CONE

Manufacturer:	R.A. Miller Industries Inc. Grand Haven, Michigan
Type:	FA-8955, Made for the FAA
Dimensions:	



Operating Frequencies:	200 - 700 MHz (Measured)
Return Loss:	13 dB typical
Operating Bandwidth: (2.0:1 VSWR)	300%
Conical Skirt:	6 Radials

Figure 2-23 Diskcone antenna data for test antenna used to determine interaction of diskcone antenna radiation patterns when located near a ground plane.

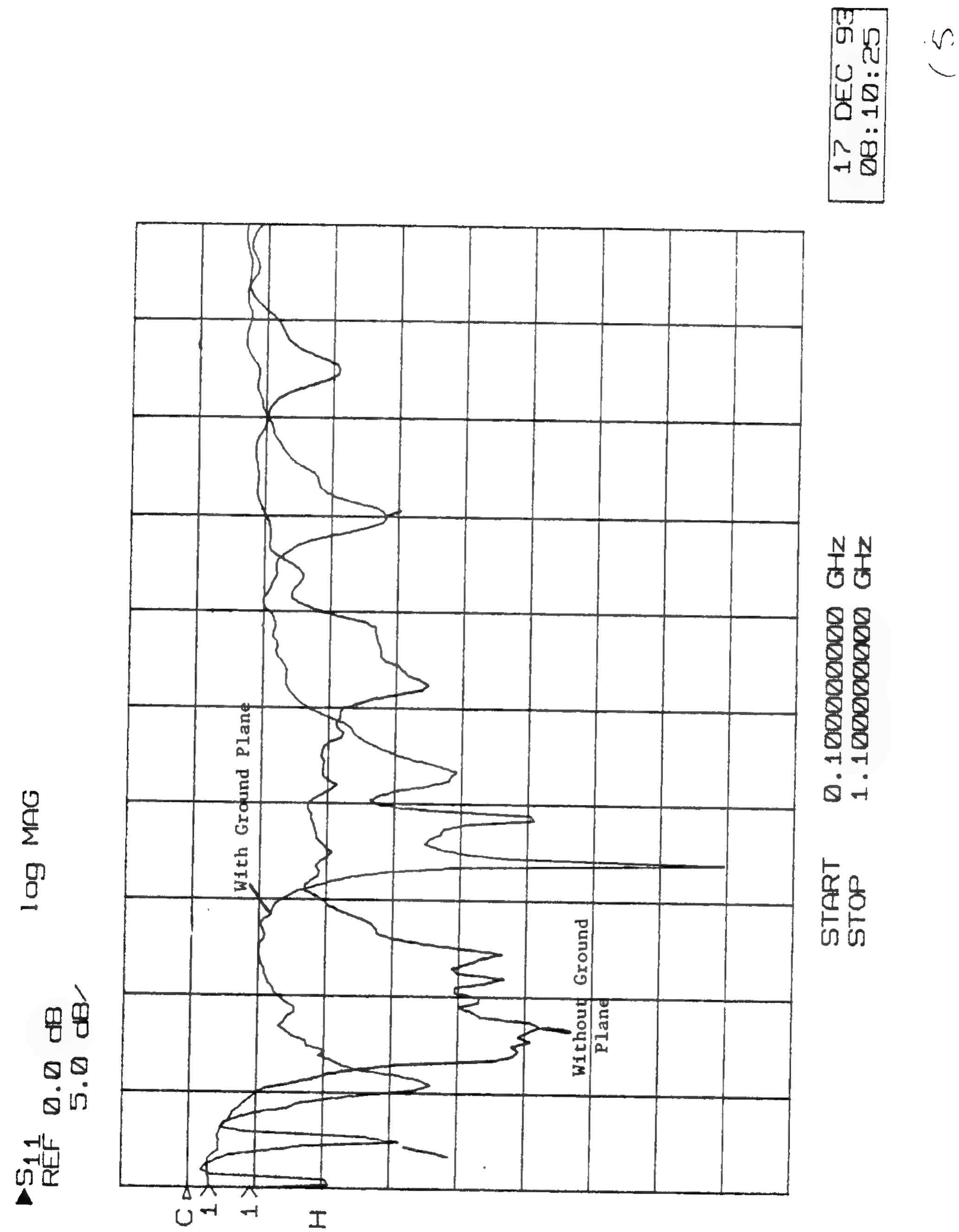


Figure 2-24. Return loss of diskcone antenna in free space and on a ground plane.

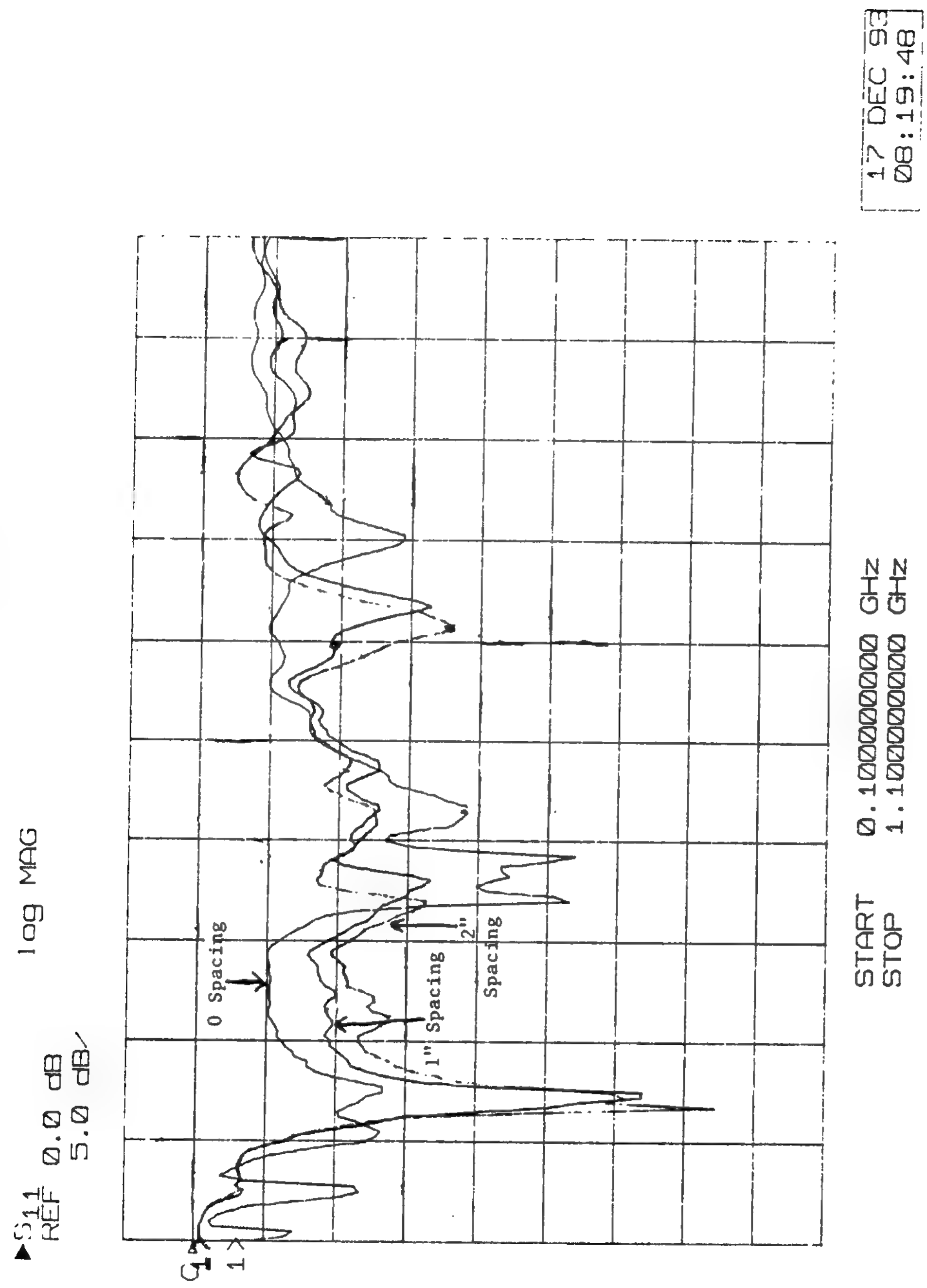
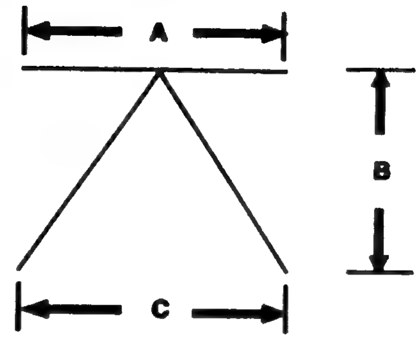


Figure 2-25. Return loss of diskcone antenna at various heights above ground plane.

DISKCONE DIMENSIONS



FREQ. BAND	BAND #	A	B	C
80 - 160	C	20.25"	33"	22.5"
160 - 320	D	12"	16"	18"
320 - 600	E	6"	8.83"	9.33"
600 - 1200	F	3"	4.91"	6.67"

DIMENSIONS OBTAINED BY MEASURING AVAILABLE ANTENN , AND DATA FROM REF 1.

REF. 1 - A.G. Kandoian, "Three New Antenna Types and Their Applications," Proc. IRE pp. 70W-75W, Feb 1946.

Figure 2-26. Design dimensions for diskcones operating in bands C,D,E and F.

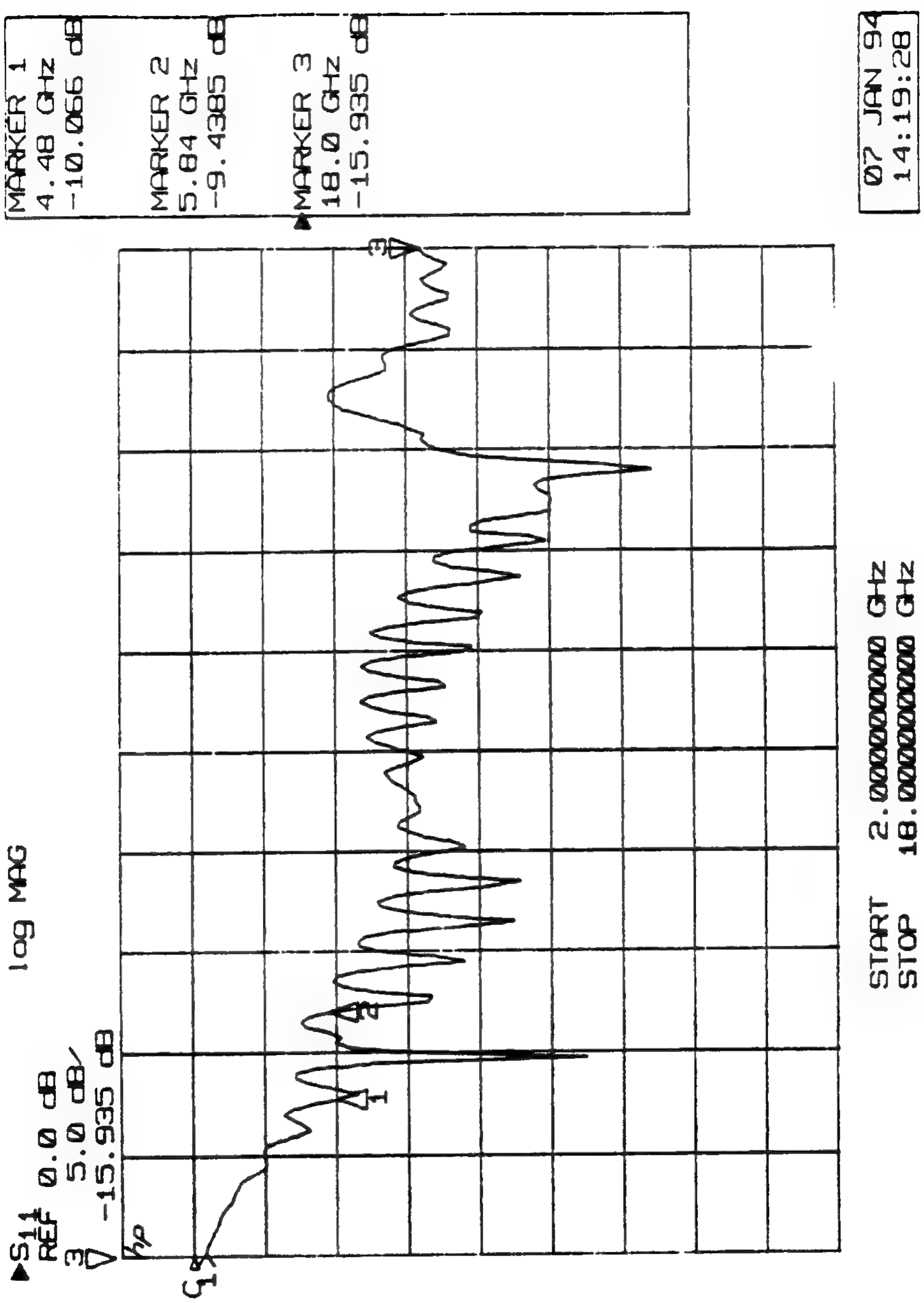


Figure 2-27. Return loss measurement of conical monopole.

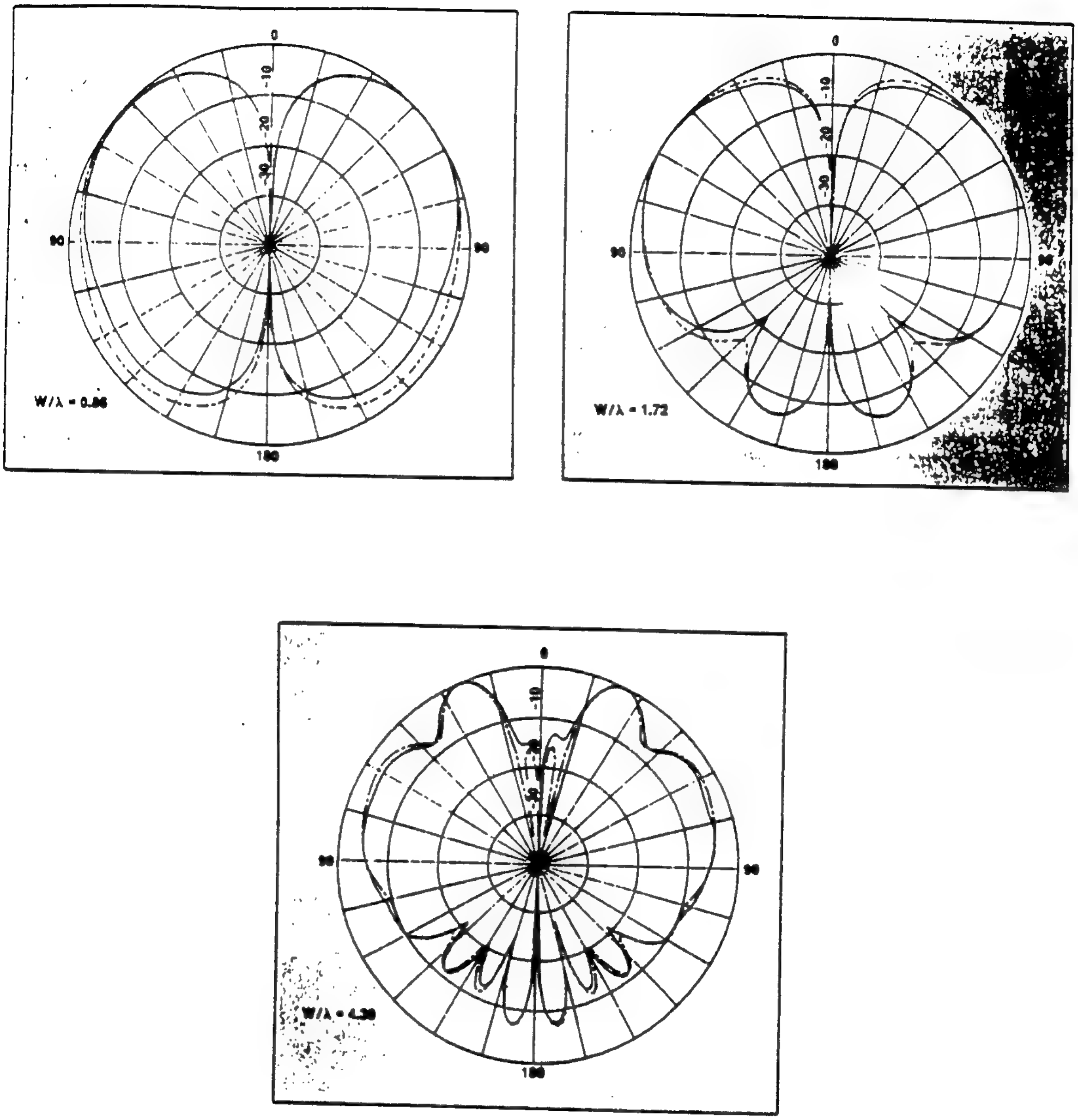


Figure 2-28. Conical monopole pattern predictions from Baker and Botha [18].

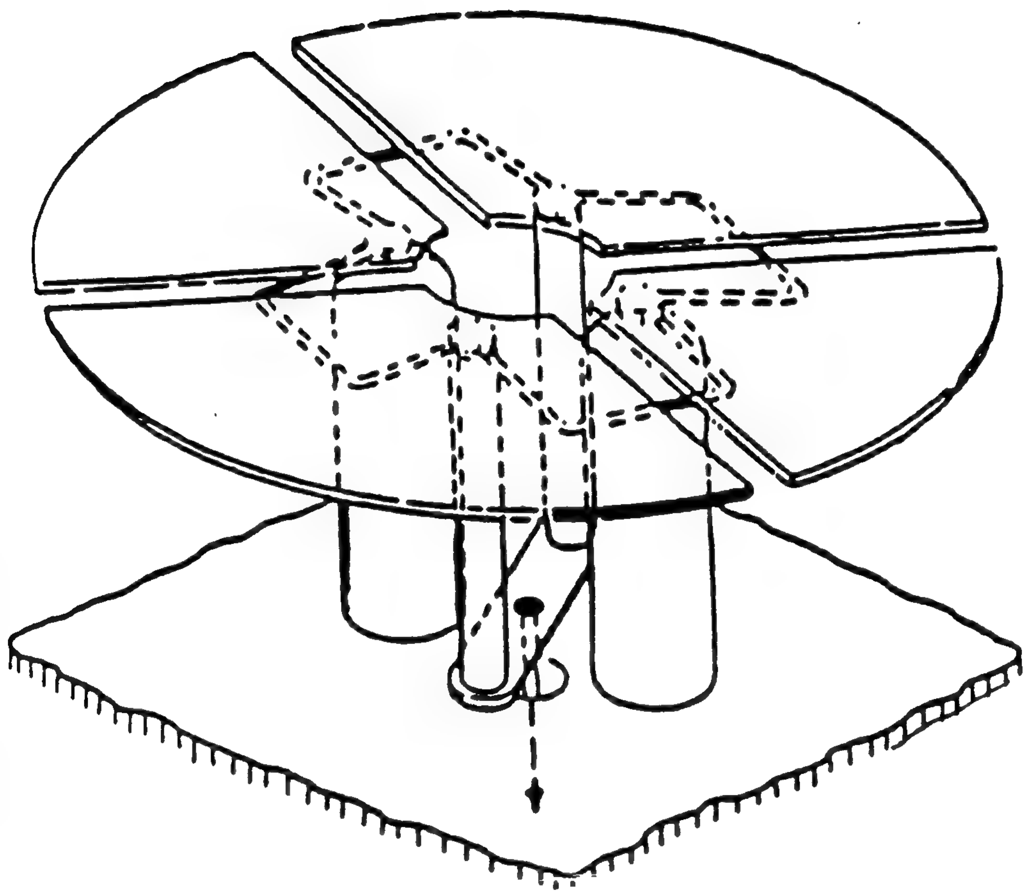


Figure 2-29. Schematic illustration of the Goubau antenna.

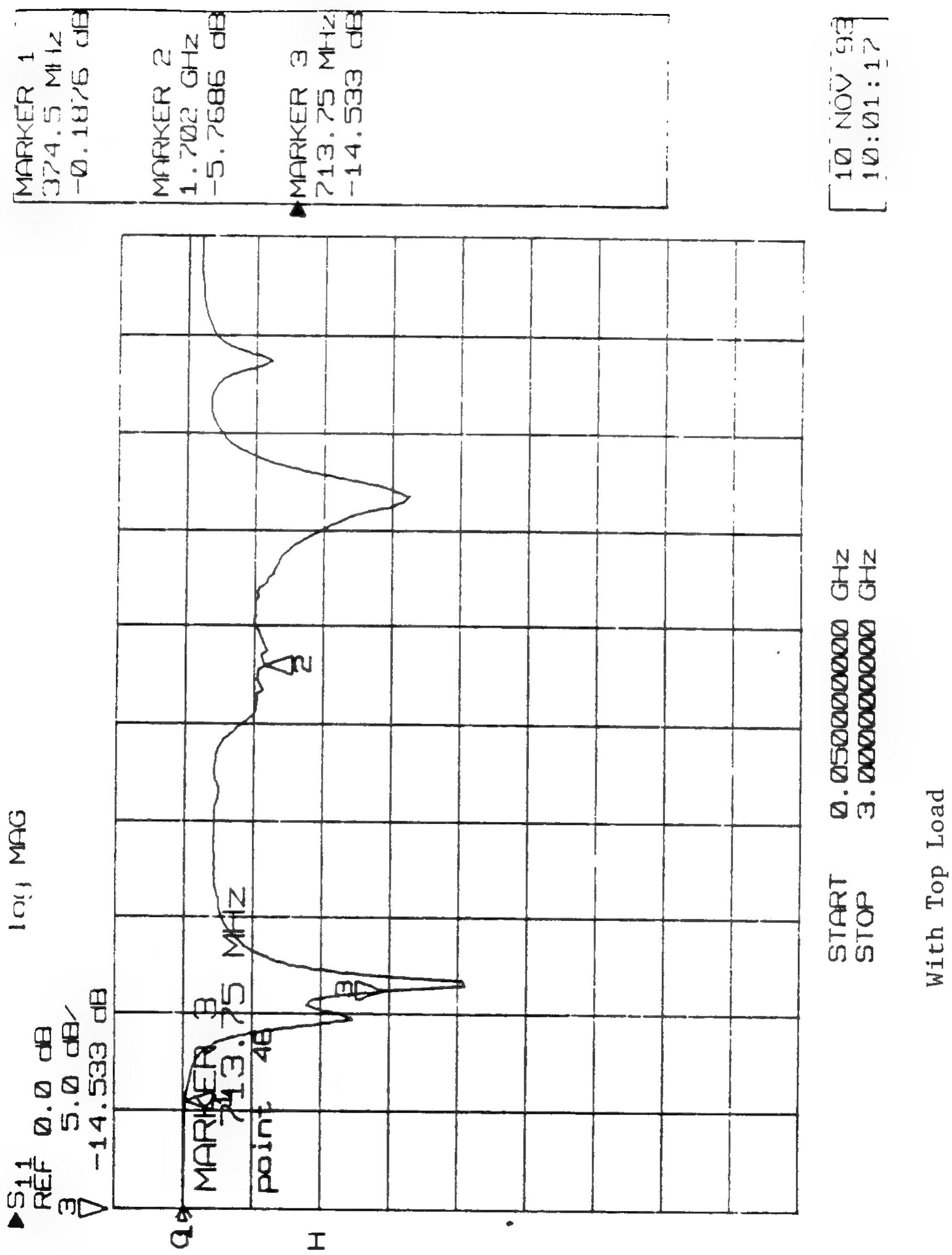


Figure 2-30. Return loss of Goubau antenna test article.

SECTION 3

SYSTEM AND PACKAGING CONSIDERATIONS

Section 2 presented a discussion of various candidate elements with broadband, low profile, characteristics which might be used to meet Navy requirements. This section presents an overview of how these various elements might be packaged into a complete system. Table 3-1 lists the various candidate antenna elements along with dimensions and volume for each element when designed for selected frequency bands. These are not the only possible options. For example, the diskcone would also be a practical candidate in the 160-320 MHz range. The use of the half-loop in the 20-40 MHz range should be considered. By orienting the half-loop along a diagonal of the 4 x 8 x 2 feet container, a half-loop about 155-inches long could be obtained. From the data presented in table 3-1, two different system configurations were postulated. System option number 1 (see table 3-2 and figure 3-1) is based on the use of a separate antenna for each band with electro-mechanical switches to perform the transmit/receive diplexing function. Total antenna volume is not a problem. However, packaging and placement of the antennas, given the two large-diameter sinuous antennas, to avoid interference and interaction would not be possible. Table 3-3 and figure 3-2 shows one option using two multi-octave antennas to reduce the number of elements. This approach, with the antenna elements shown, could be packaged in the available volume. However, it has the undesirable features of high cost and weight due to use of the ferrite substrate and superstrate. A similar approach using the half-loops above a ground plane for the lower bands should be investigated. With Option 2, placement of all of the antenna elements in the available enclosure would be feasible. Investigations into antenna interactions and interference would be required.

Table 3-1. Candidate Antenna Elements with Sizes and Volumes for Various Bands

Antenna Element	Frequency Range	Size	Volume
Sinuous Microstrip	40*-80/160 MHz	48 inch dia cylinder, 12 inches deep	12.6 ft^3
Sinuous Microstrip	80 - 160 MHz	24 inch dia cylinder, 6 inches deep	1.57 ft^3
Sinuous Microstrip with Special Material	20 - 160 MHz	48 inch dia cylinder, 5 inches deep	5.24 ft^3
Conical Monopole	160 - 320 MHz	20 inch dia cone, 18 inches high	1.09 ft^3
Diskcone	320 - 600 MHz	9.2 inch dia cylinder 9.2 inches deep	0.36 ft^3
Diskcone	600 - 1200 MHz	4.9 inch dia cylinder, 4.9 inches deep	0.054 ft^3
Sinuous Microstrip	320 - 1200 MHz	6 inch dia cylinder, 1.5 inches deep	0.025 ft^3
Half-Loop Above Ground Plane	40 - 80 MHz	12 x 72 inch dia half-loop, 2 inches in dia	0.15 ft^3
Half-Loop Above Ground Plane	80 - 160 MHz	12 x 24 inch half-loop, 2 inches in dia	0.08 ft^3

* Reduced gain in 40-60 MHz range.

Table 3-2. System Configuration Option No. 1

Band A (20-39.999 MHz)	Sinuous Microstrip with Special Material
Band B (40-79.999 MHz)	Sinuous Microstrip
Band C (80-159.999 MHz)	Half-Loop
Band D (160-319.999 MHz)	Conical Monopole
Band E (320-599.999 MHz)	Diskcone
Band F (600-1200 MHz)	Diskcone

Total Antenna Volume: 19.42 ft^3
Switch Volume: 0.027 x 6 = 0.162 ft^3
Volume Available: 64 ft^3

Table 3-3. System Configuration Option No. 2

Band A (20-39.999 MHz) Band B (40-79.999 MHz) } Band C (80-159.999 MHz)	Sinuous Microstrip with Special Material
Band D (160-319.999 MHz)	Conical Monopole
Band E (320-599.999 MHz) } Band F (600-1200 MHz)	Sinuous

Total Antenna Volume: 6.36 ft^3
Switch Volume: 0.027 x 6 = 0.162 ft^3
Estimated Diplexer Volume: 0.017 + 0.017 = 0.034 ft^3
Volume Available: 64 ft^3

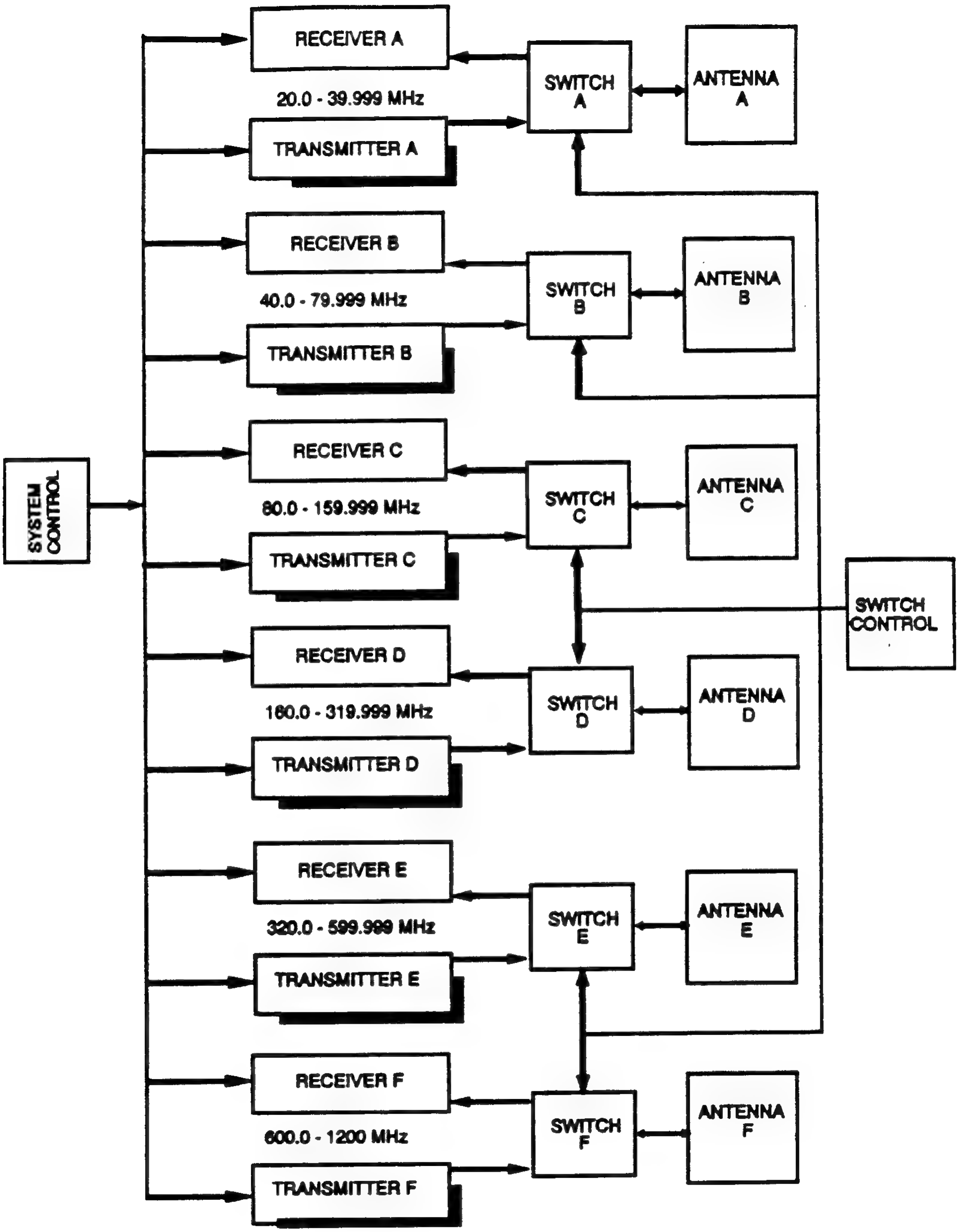


Figure 3-1. Block Diagram of Option No. 1 System

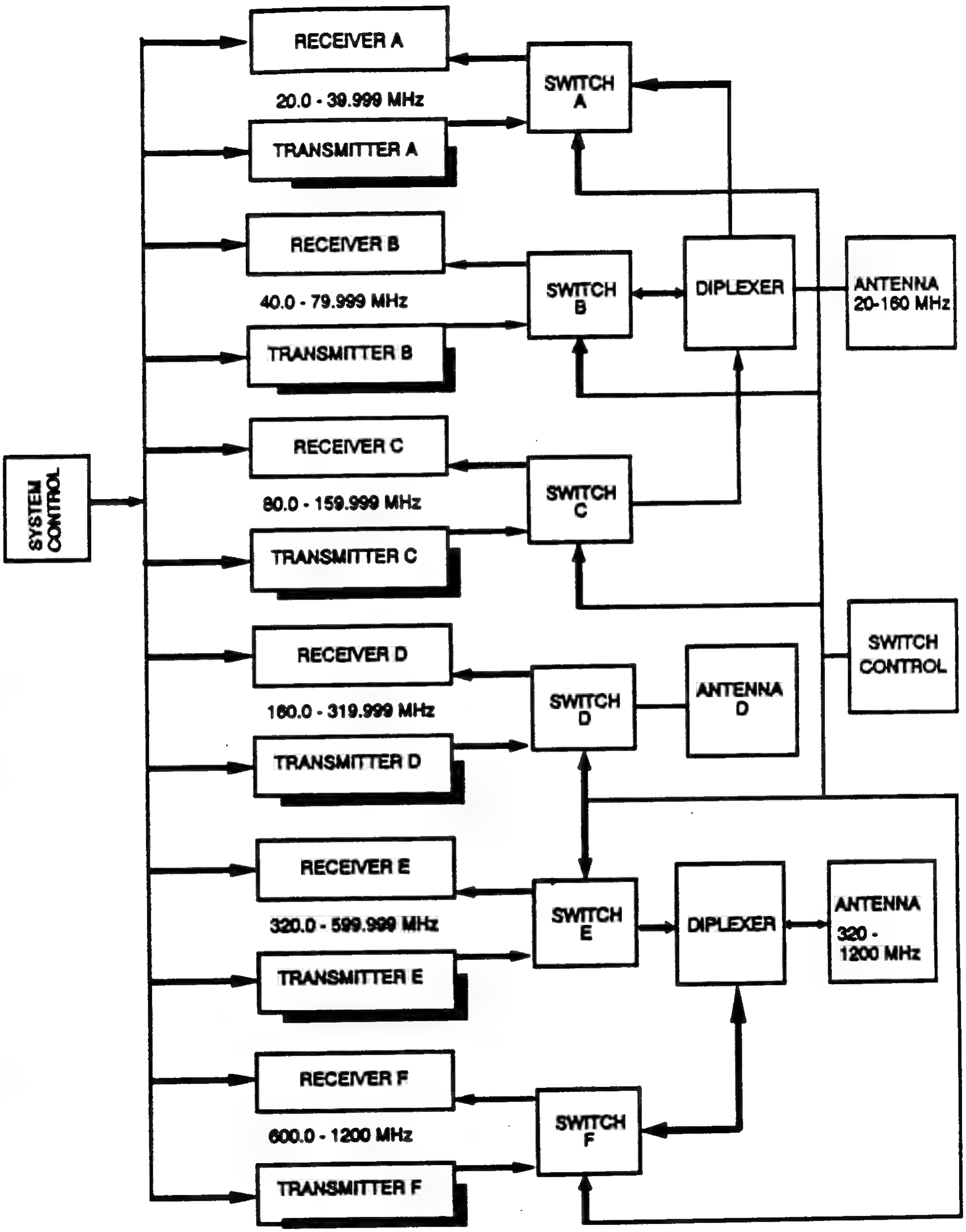


Figure 3-2. Block Diagram of Option No. 2 System

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

This report has identified, described, and characterized candidate antenna elements for broadband, low profile, antenna elements each of the Navy's bands of interest in the range from 20-1200 MHz. For bands C through F (80 to 1200 MHz), satisfactory performance with acceptable (in terms of size, cost and weight) antenna elements can be projected. In bands A and B, the situation requires further investigation. The sinuous microstrip antenna with special material loading can probably be made to work in bands A and B, but the size, weight, and cost are undesirable. Based on limited design and simulation data, the half-loop over a ground plane has the potential to work in this frequency range and fit within the available volume. However, neither prototypes nor scaled frequency versions of this antenna were fabricated, and experimental data are not available. This antenna element requires more specific evaluation.

The next phase of this program should be directed toward designing and testing antenna elements for the specific bands in which they might be applied and further characterization of elements for bands A and B. Recommendations of tasks to consider for the next phase include the following:

1. Design, fabricate, and test scaled sinuous antenna with special materials for 20-80/160 MHz band.

2. Design, fabricate, and test diskcone antenna for 600-1200 MHz band.

3. Design, fabricate, and test sinuous antenna for 600-1200 MHz band.

4. Design, fabricate, and test scaled diskcone antenna for 320-600 MHz band.

5. Model, design, fabricate and test conical monopole antenna for 160-320 MHz band.

6. Design and build scaled half-loop antenna for A/B bands.

7. Test antennas with full-sized ground plane.

8. Purchase switches and assemble at least three antennas.

9. Test system for interaction effects.

10. Test antennas at high power.

These items are not ranked according to priority. The first 6 items could be done in any order or any combination desired by the Navy. A meaningful effort involving tasks 7-10 will depend on how many of tasks 1-6 are completed. Completion of the full set of tasks should result in definite selection of antenna elements and some answers on the degree of interaction and blockage to be expected in a full-sized system.

SECTION 5

REFERENCES

1. John D. Kraus, *Antennas, 2nd Edition*, McGraw-Hill Book Company, 1988, Chapter 6.

2. Richard C. Johnson and Henry Jasik, eds., *Antenna Engineering Handbook, 2nd Edition*, McGraw-Hill Book Company, 1984, Chapter 5 (Glenn S. Smith).

3. John D. Kraus, *Antennas, 2nd Edition*, McGraw-Hill Book Company, 1988, Chapter 8.

4. Richard C. Johnson and Henry Jasik, eds., *Antenna Engineering Handbook, 2nd Edition*, McGraw-Hill Book Company, 1984, Chapter 4 (Chen To Tai).

5. J.J. Wang and V.K. Tripp, "Design of Multioctave Spiral Microstrip Antennas", *IEEE Transactions on Antennas and Propagation*, March 1991.

6. J.J. Wang and V.K. Tripp, U.S. Patent Application No. 07/695, 686; "Multioctave Microstrip", 3 May 1991, Patent Pending.

7. "Low Profile Antenna Performance Study Part II: Broadband Antenna Techniques Survey", Research and Development Technical Report ECOM-4542, C.M. DeSantis, U.S. Army Electronics Command, Fort Monmouth, New Jersey, October 1977.

8. V.H. Rumsey, *Frequency Independent Antennas*, New York: Academic, 1966.

9. R.H. DuHamel, "Dual polarized sinuous antennas," European Patent Application 019 8578, filed Feb. 19, 1986 (U.S. Patent 7 03 042, Feb. 19, 1985).

10. R.C. Hansen, Ed., *Microwave Scanning Antennas, Vol. 2, Array Theory and Practice*, New York: Academic, 1966, pp. 116-127.

11. H. Nakano, K. Nagami, S.Arai, H.Mimaki, and J. Yamauchi, "A spiral antenna backed by a conducting plane reflector," *IEEE Trans. Antennas Propagat.*, vol. AP-34, pp. 791-796, June 1986.

12. R.E. Munson, "Conformal microstrip antennas and microstrip phase array," *IEEE Trans. Antennas Propagat.*, vol. AP-22, pp. 74-78, Jan. 1974.

13. C. Wood, "Curved microstrip lines as compact wideband circularly polarized antennas," *Inst. Elec. Eng. Microwaves, Optics and Acoustics*, vol. 3., pp. 5-13, Jan. 1979.

14. "A study of the spiraphase and anisotropic substrates in microstrip antennas," Rome Air Development Center, Griffiss AFB, NY, Interim Rep. RADC-TR-85-146, Aug. 1985.

15. A.G. Kandoian, "Three New Antenna Types and Their Applications," *Proceedings IRE*, 34, pp. 70W-75W, February 1946.

16. Richard Johnson, *Antenna Engineering Handbook*, Third Edition, McGraw Hill, 1993, pp. 4-26 to 4-32.

17. S.A. Schelkunoff, *Advanced Antenna Theory*, John Wiley & Sons, Inc., New York, 1952.

18. D.E. Baker and L. Botha, "Pattern Prediction of Broadband Monopole Antennas on Finite Groundplanes Using the BOR Moment Method," *Microwave Journal*, September 1988, pp. 153-164.

19. G. Goubau, "Multi-Element Monopole Antennas," *Proceedings ECOM-ARO Workshop on Electrically Small Antennas*, Oct. 1976, pp. 63-67.

Rome Laboratory

Customer Satisfaction Survey

RL-TR-________

Please complete this survey, and mail to RL/IMPS, 26 Electronic Pky, Griffiss AFB NY 13441-4514. Your assessment and feedback regarding this technical report will allow Rome Laboratory to have a vehicle to continuously improve our methods of research, publication, and customer satisfaction. Your assistance is greatly appreciated.
Thank You

Organization Name:______________________________________(Optional)

Organization POC: ______________________________________(Optional)

Address:____

1. On a scale of 1 to 5 how would you rate the technology developed under this research?

5-Extremely Useful   1-Not Useful/Wasteful

Rating_____

Please use the space below to comment on your rating. Please suggest improvements. Use the back of this sheet if necessary.

2. Do any specific areas of the report stand out as exceptional?

Yes___ No______

If yes, please identify the area(s), and comment on what aspects make them "stand out."

3. Do any specific areas of the report stand out as inferior?

Yes___ No___

If yes, please identify the area(s), and comment on what aspects make them "stand out."

4. Please utilize the space below to comment on any other aspects of the report. Comments on both technical content and reporting format are desired.

☆U.S. GOVERNMENT PRINTING OFFICE: 1995-610-126-20017